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III b

Design and execution of welds with special consideration of thermal stresses.

Berücksichtigung der Wärmespannungen bei der baulichen Durchbildung und Herstellung geschweißter Konstruktionen.

Disposition et exécution des constructions soudées en tenant spécialement compte des contraintes dues aux variations de la température.

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IIIb 1

The Influence of Welding on Internal Stresses.

Einfluß des Schweißens auf die inneren Spannungen.

Influence du soudage sur les efforts internes.

R. Sarazin,
Ingénieur Soudeur, Neuilly-sur-Seine.

The complex stresses set up in welding steel members resolve themselves in two directions, causing secondary stresses in the metal adjacent to the welded joint which are of an indeterminate nature.

It has for some time been thought that the shrinkage of the weld-metal, in passing from the molten to the plastic and crystalline, to its final condition at room temperature, provided accurate data for determining the value of the stresses produced.

The shrinkage of an arc welded joint is composed of a transverse and a longitudinal contraction; it is difficult to proportion the stresses due to contraction of the molten metal at the weld, and those due to the welded plates and sections, which are heated to a temperature approaching fusion and subsequently cooled more or less slowly to room temperature.

We will endeavur in the present paper to discriminate between these two phenomena, for a simple case in which a strip of weld-metal is deposited on a large plate.

In welding plates or steel members edge to edge, the contraction set up in the weld-metal may cause stresses in the parent-metal, near the joint, exceeding the elastic limit, and produce permanent deformations.

Under these conditions, considering only the measurement of the shrinkage at the joint, by means of two gauge marks placed symetrically about the axis of the joint, it would be distinctly wrong to maintain the original distance between the gauge marks by hammering. We have had the opportunity of demonstrating this matter in a communication to the Congress of Autogenous Welding at Rome in 1934. The hammering sets up graver defects; the weld-metal becomes subjected to a hardening in excess of useful limits.

The inspection of a welded structure should certainly refer to the reliability of the plates or sections in the neighbourhood of the weld, and we have developed during the last five years, a simplified method of providing gauge points.

1) *Method of marking the gauge points on the structure.*

This method of providing gauge marks was described in a communication to the Welding Congress in Rome in 1934, and we will limit ourselves to giving a brief description of it, asking the reader to be good enough to refer to the report mentioned for any further information he wishes.

In the course of numerous tests we have carried out to verify the shrinkage in welded structures, we have been able to establish, that the internal stresses resulting from the shrinkage were not equally distributed in the plates, but indicated a variable distribution; the stress being nearly constant at a certain distance from the joint, and commencing to increase at about 30 or 40 cm (12 or 16 inches), becoming a maximum at the joint.

It was curious to find that in certain cases, in the course of welding, a progressive internal tension is sut up, and whith a variation in the rate of elongation a reversal of stress is detected in the neighbourhood of the joint, where compression is substituted for tension. In most cases the final layers of the weld suppress this compression, putting the joint of the structure in tension.

We have thought that this change from tension to compression, and subsequently to a tension in the region of the joint, is explained by the fact that the resultant of the combined transverse and longitudinal contraction effectively determines the rate of variation of the internal stresses.

We will see later when testing large butt welded plates, what the action is of two welding strips and what is the distribution of stress in the neighbourhood of the joint.

We have emphasised as a consequence of these studies, the marking of plates to be welded and verifying the displacement of the marks during the operation of welding. These marks require care to establish, and it is extremely difficult to distinguish differences when measuring to the thousandth part of a millimetre.

2) *Description of R. Sarazin's tensiometer.*

This difficulty has been solved by our new method of marking, which comprises adjustable pointers used in an instrument which we call a „Tensiometer", and the use of a special system of indentations.

We propose to furnish the operator, inspecting the structure with a punch which clearly marks two points at a definite distance apart. Variations are registered on the scale provided by the instrument. It is evidend that a very sensitive instrument cannot be graduated over a long stretch, and the punch permits of planing the marks to within . 1 or at the maximum . 2 mm. We have chosen for our tests a distance of 25 mm (. 1 inch) between points.

After numerous trials, we have decided upon a system of indentations which permits of absolutely precise readings, and which consists of drilling small holes 2.5 mm (. 1 inch) diameter, and 1.5 mm (. 058 inch) deep, in the centred holes produced by the punch; on these holes we impress a ball 3 mm (. 11 inch) diameter; the ball produces a spherical seating at the edge of the hole, and the points of contact of the tensiometer being themselves provided with balls, it is seen that the displacement of the gauge marks will not introduce essential error, as the spherical bearing will be practically preserved throughout the elastic period.

The tensiometer consists of a fixed portion rigidly connected with an instrument box, and carrying a special comparator and a movable pivoted part forming an arm with increased leverage, resting against a stop on the comparator. The instrument gives precise readings; each division of the comparator represents one thousandth of a millimeter, and with a little practice, one can take readings with certainty to within one thousandth.

The distance of 25 mm between the points has been chosen so that one division of the scale represents an internal stress of . 800 kg/mm² (. 48 tons per sq. inch).

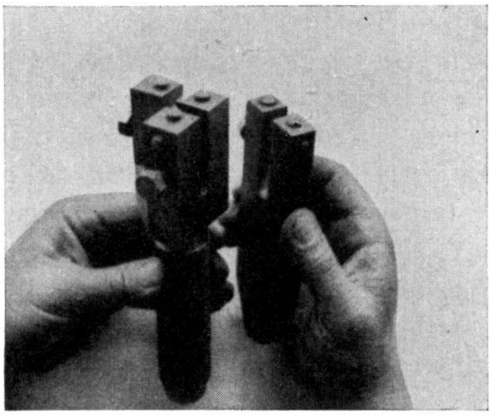

Fig. 1.
Marking tool with changeable ganging distance for the impression of test marks in two directions.

It is apparent that the instrument and the method of measuring are sensitive to variations of stress in the steel of 1 kg/mm² (. 63 tons per sq. inch) or at the maximum 2 kg/mm².

The photograph opposite shows the tensiometer held in the hand, for measuring the gauge points of the plates. The instrument hardly weighs 1 kg (2.2 lbs.), is held conveniently in the hand in all positions, and allows the taking of measurements in most inaccessible places. It has been provided with a pro-

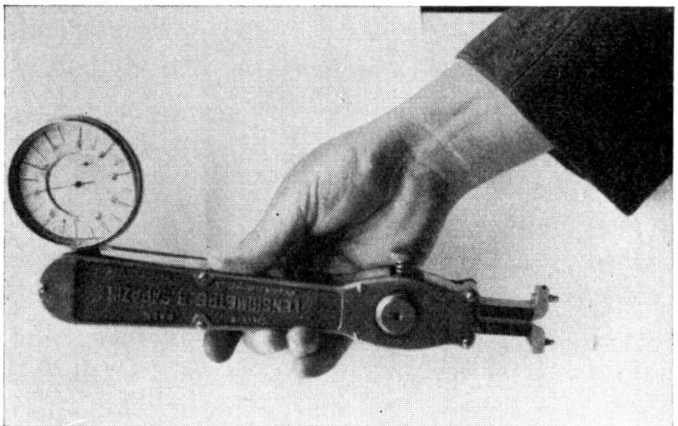

Fig. 2.
R. Sarazin's tensiometer held by operator.

jecting comparator in such a way that one is able without difficulty to work on a vertical wall where the first gauge points are situated at 15 mm (. 58 inch) from the base of the wall, as would be the case for example, in channel sections or joists.

We will further examine different cases in which the tensiometer has been used to measure the internal stresses set up by the shrinkage of the weld-metal, in order to ascertain what new phenomena are introduced by welding in the parent metal the neighbourhood of the joint.

3) *Tests carried out on a large plate after depositing a fillet of welding metal.*

The drawing opposite represents the simplest method of carrying out arc-welding, that is, the deposition of a fillet on a plate or large sheet. It is seen that the method of marking and the application of the tensiometer has furnished some very interesting facts.

Plate I shows that in forming a welding fillet on a large metal sheet 10 mm (. 39 inch) thick, a longitudinal contraction is set up amounting to a mean value of 50 thousandths of a millimetre over a length of 25 mm, which for a mild steel of 40 kg/mm^2 (25 tons per sq. in.) is in excess of the elastic limit.

This longitudinal shrinkage caused a contraction similar in direction along a line parallel to the joint and at a distance of 25 mm (1 inch) from it, which ranged from 20 to 25 mm corresponding to a local stress of about 8 kg/mm^2 (5 tons per sq. in.). In the transverse direction, the average contraction amounted to about 280 thousandths of a millimetre, considerably in excess of the elastic limit, and it is evident that in the case of a sufficiently long plate, this contraction puts the portion in the vicinity of the fillet under tension.

We have represented these several values graphically, (Curve A, Plate I), which represents the transverse deformation and (Curve C), which represents longitudinal deformation.

We have noted that in a plate 10 mm thick, the internal stresses measured on the back of the plate are of the same kind, but less in value, than those measured on the face; one can therefore say with certainty that a state of stress exists throughout the mass of the metal, which diminishes in value as the thickness of the plate increases.

We wished to observe wheter a plate 20 mm thick was similarly affected by the same phenomena, and we found that a neutral central zone existed, and the stresses on the side containing the welding fillet and on that remote from the weld, were reversed in kind.

The curve B represents the transverse variations in thousandths of a millimetre, that is, the difference between the two gauge points, when measured before welding and after the laying down of two superimposed fillets with an electrode 4 mm (. 15 inch) diameter, and a current of 140—150 amperes.

The welded specimen remained practically flat; moreover, examination showed compression in proximity to tension, which suggests a state of approximate equilibrium.

It was noticed that at the surface on which the welding fillet was deposited, a vigourous compression was set up on either side of the fillet, which despite of a thick layer of weld-metal exceeded the elastic limit, whilst locally on the side remote from the joint, a considerable tension was produced. The curves indicate the local values of the internal stresses.

It is certain that the phenomena which we have submitted, in depositing a layer of metal, are due in part, to the local heating of the plates to a temperature ranging from 1000 to 1200^0 C (1832 to 2192^0 F), and a subsequent cooling which induces contraction: The two contractions fix the value of the total compression.

The following tests will show to what extent the two phenomena interact in promoting internal stresses.

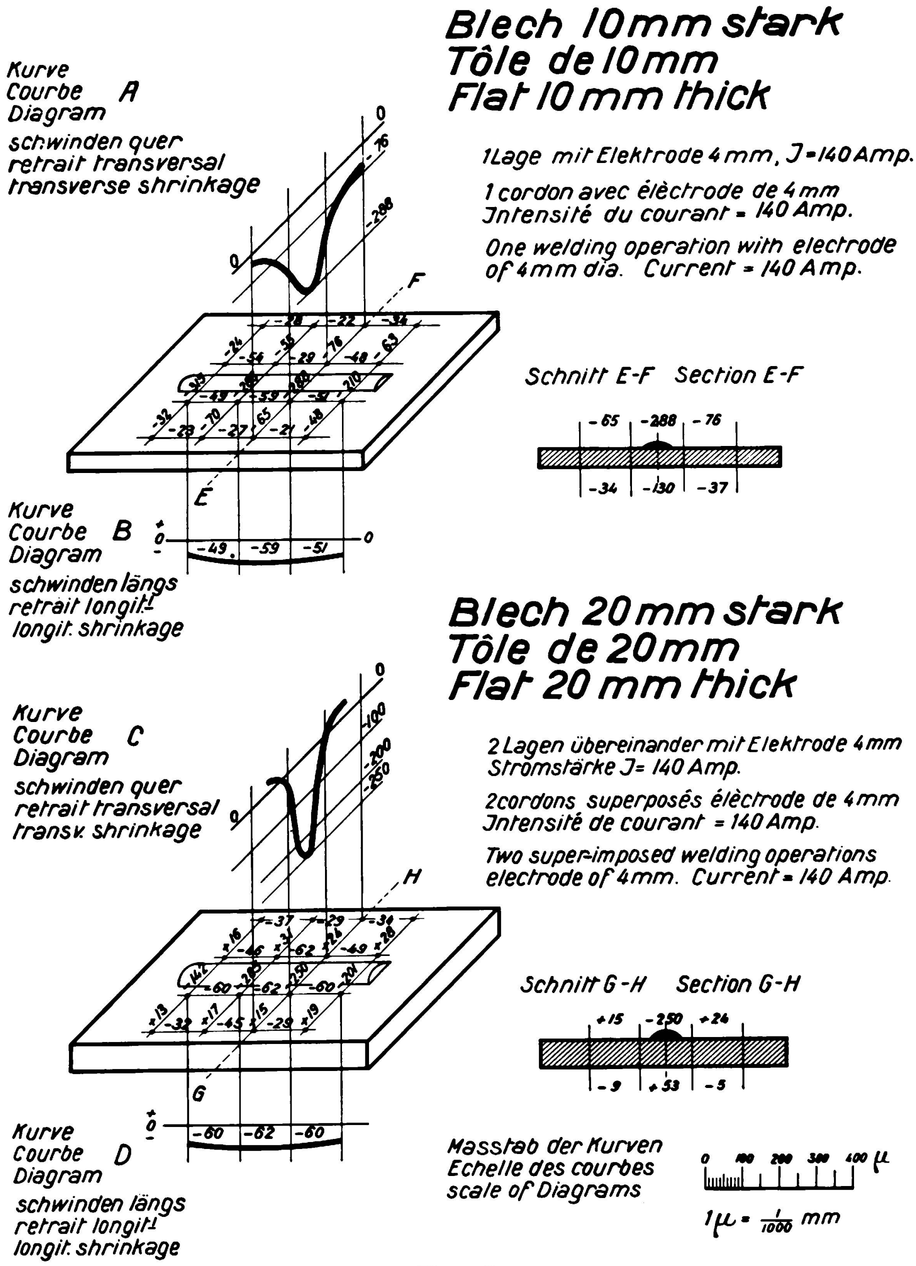

Plate I.

4) *Measurement of the shrinkage of specimens heated in electric arc, without having metal deposited upon them.*

A specimen from a plate 10 mm thick, similar to that previously used, was submitted to local heating by means of an automatically controlled electric arc, over a length equal to that of the previously deposited welding fillet.

By this procedure, the specimen assumed the same conditions as in the case of the welding fillet, and concerned only the heating of the plate, without the inherent contraction of the metal deposited by the electrode.

In order to take account of the quantity of heat absorbed in fusing the electrode itself, we reduced the current intensity of the arc from 140 to 100 amperes, used a carbon 6 mm (. 23 inch) diameter, and made a pass at the same speed as in the normal use of an electrode 4 mm diameter.

The results are given on Plate II, which indicates that the longitudinal shrinkage is of the order of 15 to 25 thousandths of a millimetre, instead of the 50 thousandths previously found, and the average transverse shrinkage is 200 thousandths as against 280 thousandths for a specimen on which a welding fillet had been deposited by the electric arc.

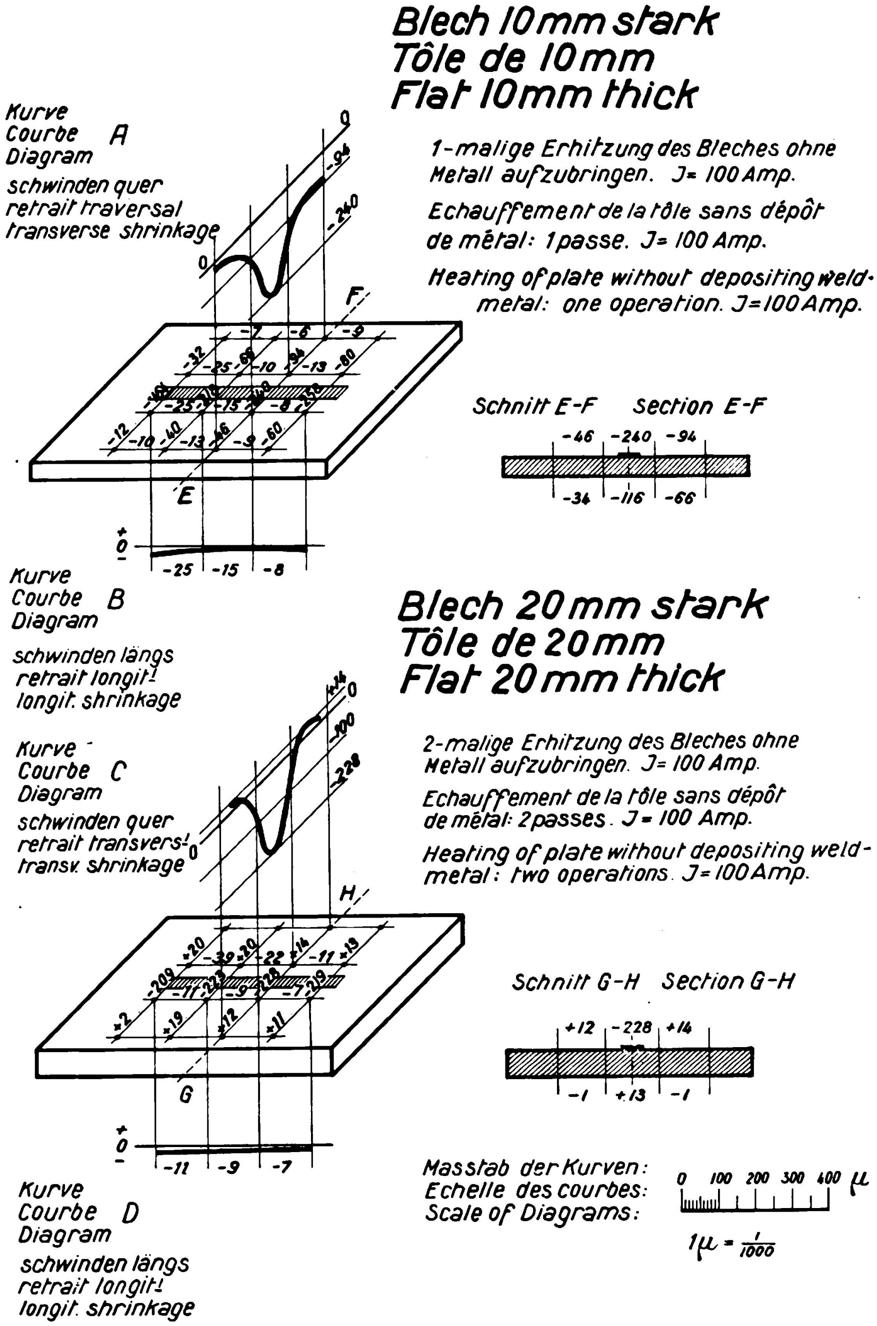

Plate II.

These figures indicate that the shrinkage of the 10 mm thick specimen represents a large part of total shrinkage set up by depositing the welding metal directly on the plate.

Two passes were also made in the manner above stated, over a specimen 20 mm (. 78 inch) thick, and it was observed that the average transverse shrinkage was 215 thousandths instead of 250 for a specimen of the same thickness, as shown on Plate I, on which has been deposited two welding fillets. The longitudinal shrinkage was only from 15 to 20 thousandths instead of 50 to 60 thousandths for the corresponding specimen.

At the back of the plate, tension was found in proximity to a slight compression.

Summarising, we can say that in depositing welding fillets on a plate, the fillet accounts for about 30 % of the deformation, the heating and cooling of the welded plate contributes the principal cause, this assertion needs verifying and is only applicable to this particular case.

5) *Determination of the shrinkage in the case of circular welding "plug" or "false rivet".*

In making this test, two specimens of steel plate 10 mm (. 39 inch) thik have been chosen, and at the centre of one of the test pieces a conical hole 30 mm

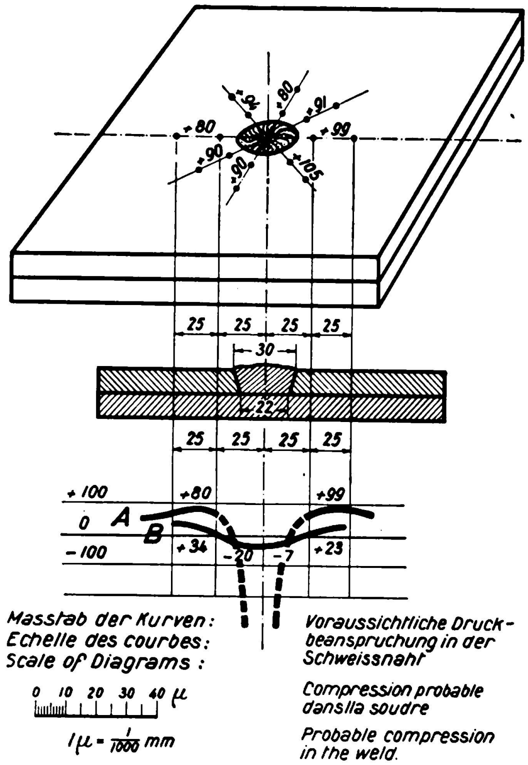

Plate III.

Welding of Hole.

Curve A: Measurements taken between marks on the front side.

Curve B; Measurements taken between marks on the rear side.

and 22 mm (1.17 and . 84 inch) diameter at top and base respectively, was drilled, the hole being thus shaped to let the arc reach the bottom plate. The welding was started with an electrode 3 mm (.11 inch), followed by an electrode 4 mm (. 15 inch) diameter, until the hole was filled.

This "plug" type of welding, or say "false rivet", is a task of precision and can give rise to many disappointents. However, it was interesting to note its behaviour from the point of view of shrinkage and see whether the axis of internal stresses followed a direction radiating from the centre of the hole.

For this purpose, the surface of the plate and the reverse side of the joint were marked as indicated. The curves given on Plate III embody the rusults.

The values recorded by *R. Sarazin's* tensiometer have given with precision the following reesults: —

On the surface the deformations consist of radial tensions and their values, ranging from 80 to 100 thousandths are consistent.

On the back of the specimen, the marks indicate at the centre a compression of 7 thousandths, and the majority of the neighbouring marks show a tension ranging from 25 to 30 thousandths. Some marks on the contrary, suggest considerable compression. (See curves A and B, Plate III.)

6) *Butt welding of two plates* (Plate IV).

The butt welding of two plates presents curious phenomena in the sense that the internal stresses are distributed in a manner dependent upon the ratio of the thickness of the specimen to its width.

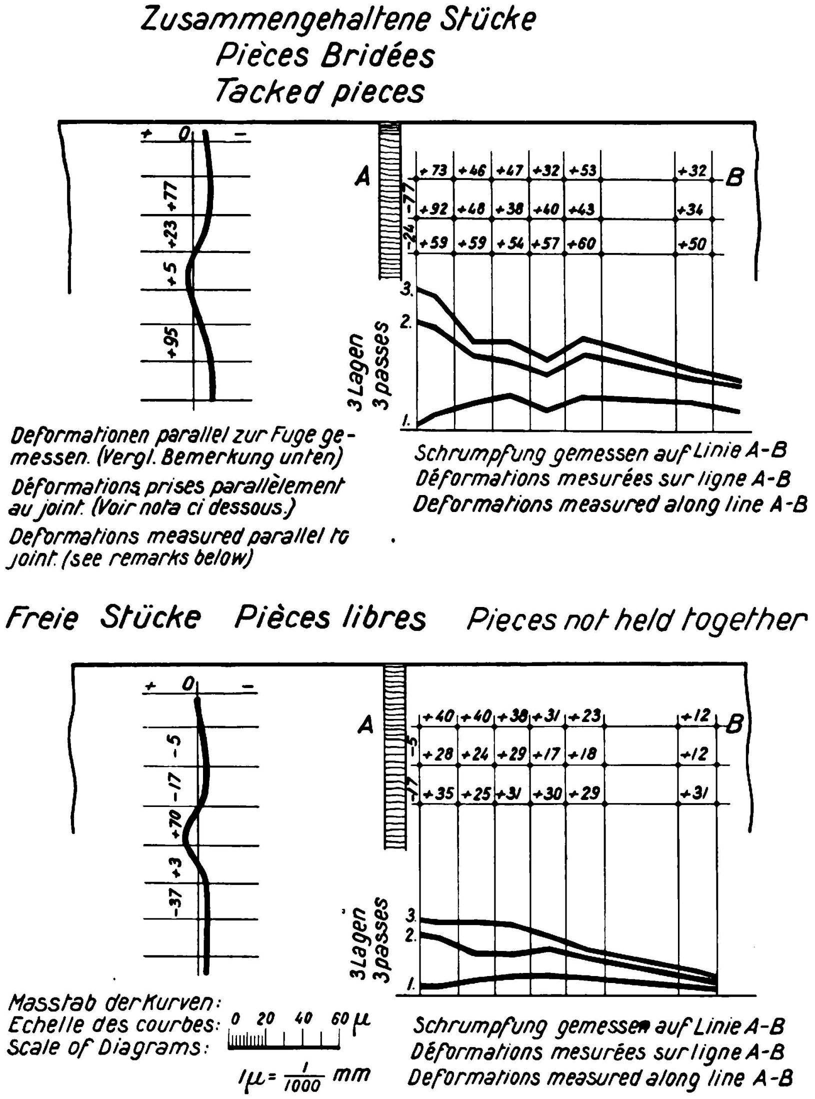

Plate IV.

Butt-welding of two plates of 250 mm width and 8 mm thickness. Note: The change from tension to compression is explainable by the small width of the test specimen.

The longitudinal contraction, in conjunction with the transverse contraction and the conditions of working, develop characteristic results.

In the case of plates 8 mm (.31 inch) thick and 250 mm (5 inches) wide, considerable difference in the stress and in its distribution occurs when the plates are free and when held together by welded tacks.

The curve on Plate IV shows the distribution of stress in free plates, and it is seen that at 25 mm (1 inch) from the joint on an axis perpendicular to the joint, a maximum tension ranging from 20 to 24 kg/mm² (12.6 to 15.1 tons per sq. in.) occurs. The first pass sets up a tension, increasing in the neighbourhood of the joint, reaching its maximum at the welding fillet.

At the second pass the tension increases and the curve is deflected in the region of the joint; this is no doubt due, as we have said, to the interaction of the longitudinal contraction, which neutralizes a portion of the tension.

At the third pass, the deflection of the curve is modified and emphasises the increasing value.

Summarising, it can be said that in a large plate 8 mm thick at a short distance from the joint, about 200 mm (8 inches) from the free welded joint, the general tension is about 8 kg/mm² (5 tons per sq. in.), at 100 mm (4 inches) the average tension is 10 kg/mm² (6.3 tons per sq. in.) and at 25 mm (1 inch) from the joint a maximum tension is reached of 20 kg/mm² (12.6 tons per sq. in.).

On similar specimens held together by welded tacks, that is, welded at the ends when rigidly held on a large slab, the values were much higher. At 200 mm the general tension ranged from 10 to 12 kg/mm² (6.3 to 7.5 tons per sq. in.), at 100 mm the average tension was 20 kg/mm² (12.6 tons per sq. in.) and at 25 mm from the joint. The maximum internal stress ranged from 30 to 35 kg/mm² (18.9 to 22 tons per sq. in.) which exceeds the elastic limit of normal mild steel.

The longitudinal deformation, on a line parallel to the joint and at a short distance from it, often shows inconsistencies, which will study more closely in future; we have noticed in fact, that the deformations occur where points, in close proximity to those under tension, are under compression. It will be interesting to determine a reason for these discrepancies, because an approximately uniform contraction has been found in specimens of greater thickness.

7) *Lap-welded plates* (Plate V).

This type of joint, known as "covered" or "lapped", reproduces the rivetted joint. It has been used since the early days of welding for joints in naval construction and is used in some cases for the welds in structural framework.

This joint is not always advantageous, because it subjects the weld to transverse shear and requires a heavy deposit of metal which makes it uneconomical.

However, it is interesting to see how the welded members react, and two large plates 10 mm thick have been welded, which were previously marked, as was done in the preceeding work. Plate V represents the welded specimen and between each pair of points we have inserted two values; the first refers to the reading taken after the weld AB had been made in three passes with electrodes 4 mm diameter and a current of 140 amperes.

The values arrived at after this first weld have shown that lapping the line of the joint set up a compression of about 40 thousandths of a millimetre along the edge of the specimen on the left and a compression of about 20 thousandths of a millimetre across the specimen on the right.

It will be noticed that the two compressions have added to the tension existing along a line perpendicular to the joint; this extension being due, on the one hand, to the transverse contraction of the joint, and on the other hand, to the longitudinal contraction of the deposited metal. In fact, this latter contraction in shortening the plate transversely, sets up an elongation in the immediate vicinity.

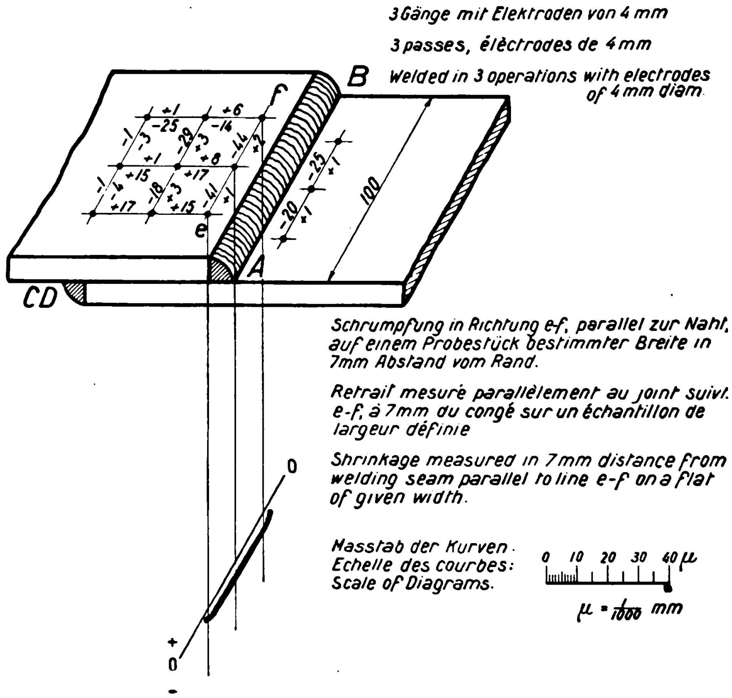

Plate V.

Welding of a lap-joint of two plates 10 mm thick.

Remark: The 1st figure between marks indicates the longitudinal deformation after execution of weld AB. The 2nd figure stands for deformation after welding of line CD. The 2nd figure has to be added to the 1st to obtain the final state.

After the weld AB was finished, that on CD was made under similar conditions, and fresh measurements made, which have formed the object of our preceeding readings.

We have noted a fresh discrepancy which has slightly modified the first readings. It will be seen that this must be added arithmetically to the value already existing, to give the final state of the joint after welding.

The measurements made on a line parallel to the joint have shown that the compression was fairly regular as is shown by the curve (Plate V).

8) *Welding two plates at right angles to each other* (Plate VI).

Plate VI shows this particular case, which is the one most generally met with in structural framework. It was interesting to ascertain the distribution of stress over the different members.

For this purpose the base was marked on the front and back surfaces, and similar marking was effected on both sides of the plate forming the web. The marks were uniformly spaced 25 mm apart by means of the special punches.

The tensiometer, being adjustable about its base it was possible to place marks 15 mm (. 58 inch) from the angle, that is, 5 mm from the edge of the fillet; thus the measurements have been so much the more characteristic. In a general way it does not appear that this type of joint gives large deformations in the web and upper surface of the base, but the back of the base plate, that is, the surface remote from the weld shows considerable tension, which is, moreover, noticed by a tendency of the plate to deflect.

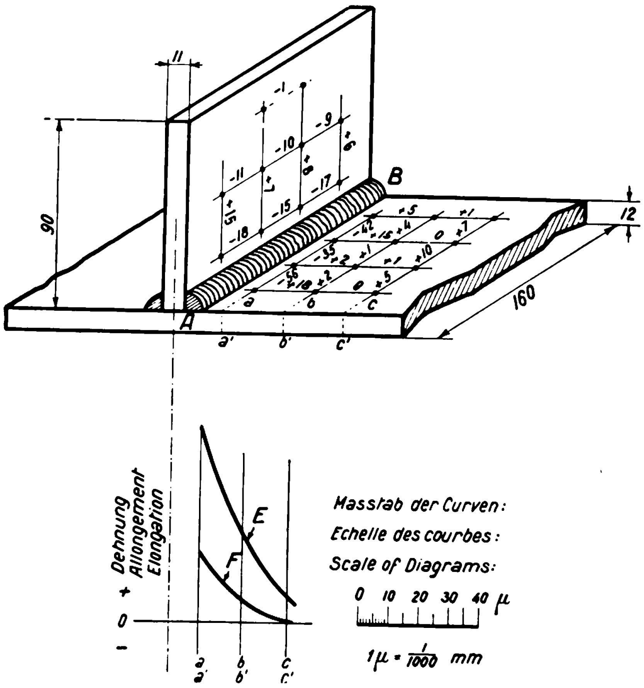

Plate VI.

Fillet weld connection of two steel plates, 3 lagers, 4 mm electrodes. Amperage 140 amps. The welds AB and CD have been made in turn.

Note: The base plate was marked on both sides. The curves E and F show values of deformations.
E: for deformations measured on the rear side at right angles to AB.
F. for deformations measured on the front side at right angles to AB.

The angles containing the welding metal tend to close up, but for rigid pieces this difficulty does not occur.

From an examination of the values recorded on base plate and web, one notices that the contraction is not so great on the latter. It would be necessary to make further experiments on plates of various thicknesses, to ascertain the cause.

9) *Use of the tensiometer for the determination of stresses in a welded structure.*

From the evidence we have put forward, it may be thought that the investigation of the internal stresses of a structure involves a very precise and costly system of marking. It is not so, because for industrial use one is not obliged to make numerous markings, and from our experience in the use of the instrument, 3 or 4 imprints of the punch in 3 directions set out along the line of the joint suffice to give 12 distances, therefore 12 measurements, which amply suffice to determine the magnitude of the phenomena.

In practice, for the investigation of stresses it will not be necessary to make the imprints on the face and reverse surfaces of the welded plate, because we have seen that if the plates are less than 10 mm (.39 inch) thick, the deformations will be less than one half of those recorded for the surface on which the weld was made, and that if the plates are more than 20 mm (.78 inch), these deformations may be reversed in kind but their value will be very small.

The use of the tensiometer in the course of welding a structure will avoid the troubles arising from the shortening of a line of joint, especially if it is a long one, in which it may lead to a diminution of 1 mm per metre, which for a bridge girder 10 metres long (33 feet) would be a shortening of 10 mm (.39 inch) in some places. This can be prejudicial to erection or to the proper distribution of the load.

Controlling the stresses in course of construction will avoid putting parts of the structure which should work in harmony, under different conditions of stress, and for example, in a symmetrical structure, we think that by this method the welded structure could be left in such a state that the shrinkages would be judiciously distributed.

It is evident that for the calculation of tensions set up by the welding, elastic deformations only should be accounted for and these are easily calculated by Young's formula.

Summarising, we might say that there are usually some points in the elastic welded structure in which the metal is stressed beyond the limit. In our opinion, this point is not important because the structure rapidly attains a state of equilibrium in consequence of the stresses produced by its normal working loads.

Some authors contend, no doubt with reason, that exceeding the elastic limit has the advantage of orientating the crystals in the direction of stress and it can be easily shown that the slight hardening which results is without practical effect on the mechanical properties of the steel.

10) *Modification of the internal stresses.*

The method of marking that we propose, and the instrument we have described, serve to demonstrate in a precise manner, the distribution of internal stresses in the members of a joint and in varions parts of the welded structure.

There often exists means of decreasing the internal stresses, and we will endeavour to bring forward in the future some methods of welding, which will reduce them to a minimum.

We can, in fact, make the following recommendations which are of a general character:

In welding a structure, the members forming it should first be assembled, and the start made by welding those members which can be butt welded in such manner that the deformation is a minimum, such as is shown on Plate IV when the pieces are free.

Right-angled welds are then made which, for example, concern the connection of flange and web, and as a general rule the right-angled welds are made of just sufficient strength for the stresses to which they are subjected, so as to avoid a considerable longitudinal shrinkage. Concerning this subject we have noticed that the right-angled welds are often so much too heavy and represent a degree of safety so much too high, that it justifies the preceeding remark.

When a long length of weld has to be made, it is always advisable that several welders should work along the same line of the joint and if the pieces are thick and access to both sides possible, it will be useful to provide a double chamfer by setting the welders to work on each side of the joint. This practice will be advantageous from the point of view of decreasing deformation.

Some engineers are concerned, by the magnitude of the internal stresses set up by welding, but we reply that rivetted structures are not exempt from internal stress and that often the use of a drift or faulty rivetting will set up stresses which we consider analogous to those indicated by our tests. We feel compelled to mention these facts.

There is occasion to draw the attention of welding engineers to a particular point which concerns the weldability of steel used for structures. As a general rule, all the usual commercial steels can be easily welded. However, for structures having a large margin of safety, as for instance, bridges, it will be well to insist that the steel should be weldable in conformity with the researches carried out in this particular branch, and in deciding between two steels suitable for use on a contract, preference should be given to the one which, after being stressed beyond its elastic limit and submitted to a fresh tensile test, is further elongated before rupture. This property must, of course, be considered in conjunction with the mechanical properties, specified for the type of work to be welded.

There are various means of decreasing the deformations, such as: — the choice of electrode, the choice of current intensity for a given electrode and lastly, for a given type of electrode, the choice of diameter to be used.

In welding with electrodes of small diameter, the welding metal is deposited in small successive deposits, giving rise to a series of shrinkages, which set up considerable stresses in the neighbourhood of the plate.

In welding with electrodes of large diameter and high intensity of current, a large area is heated and the concentration of metal too localised; the member is red hot for a longer time, the metal expands and an insignificant local shrinkage can be detected; probably due to the fact that a large area has been annealed by the immense heat of the arc and this presents some difficulties. The choice of the best diameter of the electrode will therefore merit some preliminary tests on the lines we have suggested.

Lastly, there exists another method of drecreasing the internal stresses; that of hammering after each layer of deposited metal. The hammering being methodically carried out in such a way that the amounts of shrinkage recorded by the gauge marks is modified at each pass to the preceeding values or a value approximating to it. We have shown in our report to the Congress at Rome (1934) that such hammering can neutralize almost completely the internal stresses provided that the hammering is carried out with care to prevent a useless hardening of the deposited metal.

We have also shown that a slight hammering of the edge of members welded together, effectively neutralizes the stresses, and we have given exact indications of the work expended for given test pieces.

From our experiments an important point arises as to the quality of the welding metal. The electrode should yield a sound and homogenous deposit, possessing good ductility and resilience; the metal deposited should not show cracks when forged hot or when cold-hammered.

11) *Use of the tensiometer to determine the working stresses in structural framework.*

A number of experiments have been carried out to discover under what other circumstances the tensiometer could be used similarly to an extensometer of the usual type. Possibly our instrument may be a little less exact than certain

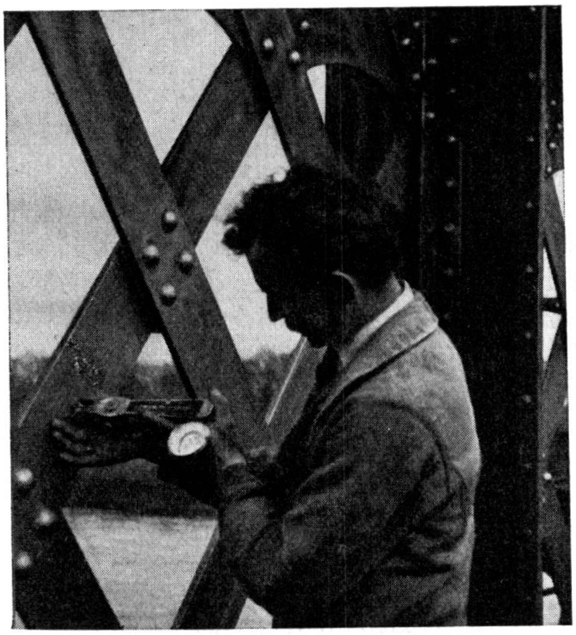

Fig. 3.
Fixing of Tensiometer to diagonal of a riveted bridge for measuring stresses under traffic.

extensometers, but on the other hand it has the great advantage of being able to be mounted at any point of a frame and in any position, when using it in conjunction with the method of marking as proposed and with a system of imprints.

We have been able to read, for example, during the passage of a train, the changes of stress in a diagonal, and it was found that at a certain moment the working stress varied from 5 kg/mm^2 (3.1 tons per sq. in.) below the stress due to dead load, to 7 kg/mm^2 (4.4 tons per sq. in.) above the stress due to same.

The instrument was not effected by the considerable vibration set up by the passage of the train, and we have been able to use it when held in the hand, and when placed on a small support of a type represented in the photograph opposite.

The tensiometer could therefore be used to determine the working stress in structures or even in machine parts, and we can cite the example of taking the stresses in the swan neck of a steel press, where each compression caused a deflection of the scale pointer indicating a maximum range stress of 10—12 kg/mm^2 (6.3 — 7.5 tons per sq. in.).

This shows that we can also on welded machine bodies investigate into the nature of stresses at places subject to important forces. These stresses are mostly very difficult to calculate and consequently remain practically uncontrollable, therefore the research offices demand always increased sections.

By the use of the tensiometer in this case, any part of a machine can be exactly proportioned to the stresses for which it is calculated, and at the first trials of the machine, it can be ensured that the ranges of stress do not exceed those which have been provided for.

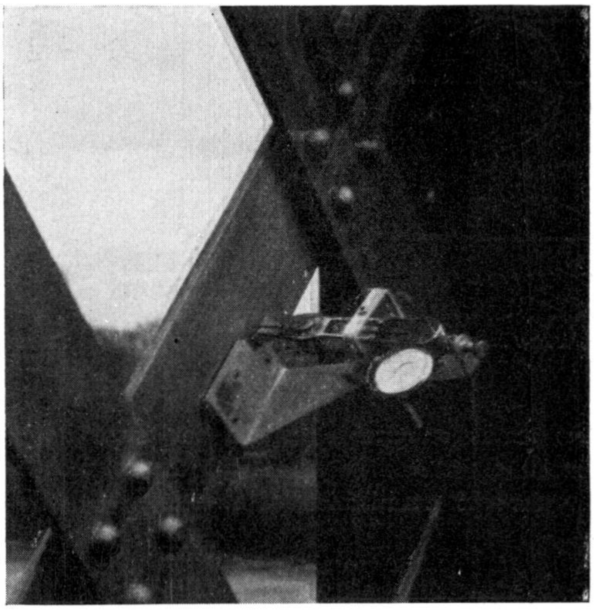

Fig. 4.
Fixing of tensiometer to diagonal by means of angle iron bracket, to give instrument increased stability.

12) *Maintenance of metal structures.*

The system of gauge marks which we recommend for the construction of bridges, trusses and other structures, ought not to be neglected after the structure is finished. In fact, if the precaution is taken to cover the indentations immediately they have been made by a simple device consisting of an oiled washer of felt and a screwed metal cap, in such a way that the indentations are well hidden, one can periodically take fresh measurements by opening out and cleaning the indentations.

The tensiometer can then be applied successively at various points of a structure, and the values between the gauge points tabulated.

In taking fresh measurements periodically every two years, it can be ascertained whether the stresses at any point are dangerous and whether any parts require special attention.

We hope that this small study will contribute to the improvement of arc-welding, because we consider that with a better understanding of the factors which control this process of welding, engineers who can make use of it will appreciate and recommend more warmly its use.

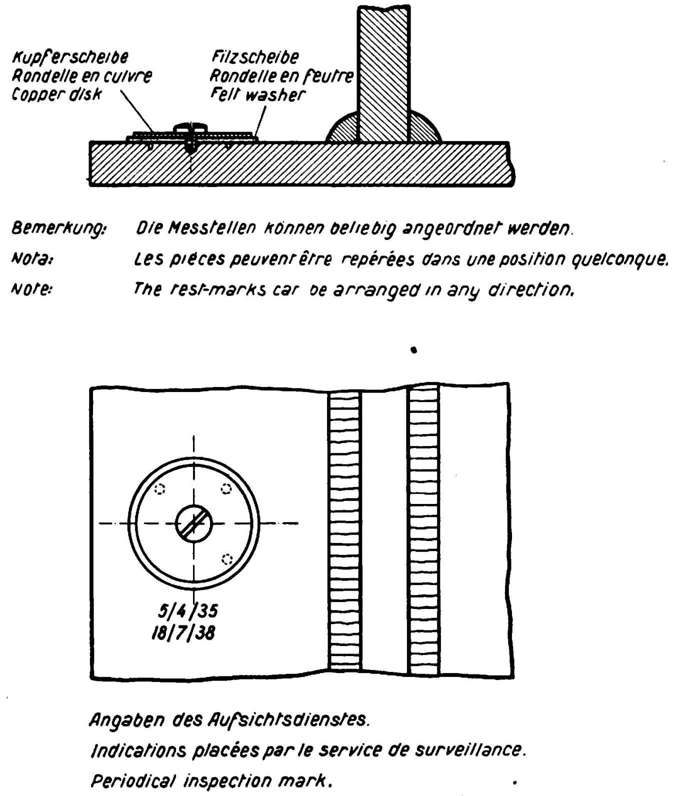

Plate VII.

Preparation of test marks on steel structures for inspection purposes. Note: Periodical measurement will be taken with the original test marks for the examination of stresses.

Summary.

The author describes in his report an apparatus of his own invention, based on the principle of comparison, for measuring deformations. Before welding is done a measured length is marked by small impressions. Before and after welding the tensiometer is placed on these impressions, which are in pairs. The report contains the descriptions of experiments carried out with different types of welds. The deformation due to heat and cooling are measured parallel and at right angles to the welds. The measured values are plotted and shown in diagrams, the stresses brought into relation with the distance from the weld, for which the deformation can easily be measured.

The *R. Sarazin* tensiometer can also be employed for taking measurements on existing steel structures; and it has the advantage compared with other instruments of easy application, that it can be used without special fixing arrangement. The measuring marks can be covered by oiled felt pieces and a protecting metal disc, so that they can be used for taking measurements at later dates.

IIIb 2

Design and Execution of Welded Structures.

Ausbildung und Herstellung geschweißter Bauten.

Projet et exécution des ouvrages soudés.

A. Bühler,
Sektionschef für Brückenbau, S. B. B., Bern.

I. Nature and Measuring of Heat and Shrinkage Stresses.

1) The Nature of Heat and Shrinkage Stresses.

In the detailing and manufacture of welded structures, the heat stresses produced by the welding process and the subsequent shrinkage stresses due to cooling demand special attention. When a joint is welded, a large amount of heat must be introduced locally in order to connect weld metal and parent metal by fusion.[1]

In heating the material in the region of the joint, it expands, whilst that lying farther off, remaining comparatively cool, hinders the process of expansion. In the proximity of the joint compression and straining of the material is set up, assisted by the heating, whilst the remaining cross section of a specimen is subjected to bending and tensile stresses, and, in limited cases, may even be stretched.

The cooling of a hot joint and with it the surrounding parent metal, is followed by a counteracting internal resistance of the cooler metal more remote from the joint after these portions have lost their bending and tensile strains. This process finally causes the joint and its immediate vicinity to become subjected chiefly to internal tensile stresses, whilst correspondingly other contiguous parts have to withstand compressive strains. The eccentric position of a joint in respect to the axis of the bar, and the constant occurrence of unequal heating, can cause considerable differences, disturbances and changes in the flow of stress, with the result that a linear distribution of stress no longer exists, especially in the weld metal and its immediate vicinity[2].

Besides, permanent deformations develop in the weld metal itself and in the contact area between weld and parent metal. Some parts of the material shrink and subsequently stretch again. The deformation of parts of the bar owing to welding, often considerable, prove the existence of high internal stresses[3].

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[1] *Wörtmann:* Schweiz. Bauzeitung 5. XI. 32, Transference of heat: 1150 k cal/kg of the weld metal; the quantity of heat must be dependent on the number of welded layers and the dimensions of the parts to be welded.

[2] *Bierett:* Tests to determine shrinkage stresses. Z. V. D. I. 9. VI. 34.

[3] *Reinhold* and *Heller:* Indications of shrinkage in the electrically welded Schlachthof Bridge at Dresden.

These characteristics remain in general the same when joining girders of component parts or trussed steel structures composed of different members. In the latter case, in addition to the internal stressing mentioned, stresses occur which develop from the reciprocal coercion caused by changes in the length of the members and girders. This fact has to be particularly watched in the strengthening of bridges.

It is clear that under such circumstances the heat stresses and subsequent shrinkage stresses can only be approximately determined, since the deformations lie partly in the plastic region. It is therefore not surprising that materials used in welding must have a high elongation if fractures are to be avoided. (Fig. 1.)

If necessary, welded parts can be more or less heated after welding, or be annealed and subsequently slowly cooled, so as to reduce or nullify the internal

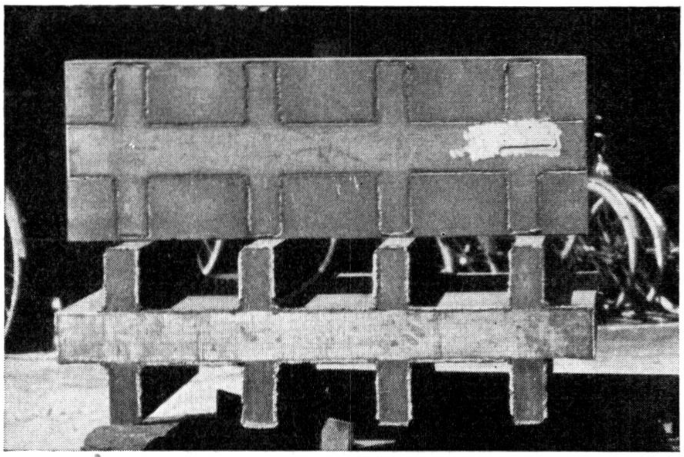

Fig. 1.

Failure in welding a rail-steel plate to steel St 37. After cooling the welds broke out of the high carbonsteel.

stresses. Yet these processes are not often employed, and, in the case of smaller workshops that carry out most of their work with welding, are usually impracticable[4]. It is, however, chiefly the small and medium-sized workshops that go in for electric welding, for the equipment required is not very expensive and is permanently ready for operation.

Under certain circumstances it is of great advantage in the cases of thick pieces to weld them in a warm condition (100° to 300° C, i.e. 212° to 572° F.)[5]. If preheating can be effected without inconvenience to the workmen, it ought to be possible to reduce the shrinkage stress considerably by welding in this condition.

2) *Devices for Measuring Heating and Shrinkage Stresses.*

The measuring of heat stresses has to my knowledge been but seldom undertaken, because it is difficult to work with sensitive instruments in the zone

[4] The penstocks with plates up to 45 mm (1.77 in.) thick at the Etzel water-power station were annealed at a temperature of about 630° and maintained at this temperature for 6 hours. By this means the internal stresses caused by welding and the unfavourable structure of the weld joint (Widmannstätten structure) were neutralised. The welds made at site were also annealed.

[5] *Escher-Wyss* Ltd. Memorandum N° 5. May 1928.

of the weld; also, the loss of heat in the air and the flow of heat in the bar itself cause the stressing conditions to change quickly and continuously. Nevertheless, extensometer measurements will show to a certain extent what is taking place in the bars about to be welded.

It is essential for the designer of a structure to know the shrinkage stresses remaining after the equalisation of heat with the surroundings. These can be approximately determined in different ways, namely by: —

a) Measurement of the change in distance between two points before and after welding.

b) Borings and measurement of the expansions set up in the neighbouring material (Mathar)[6].

c) Measurement of the lattice spacing by X-ray methods[7].

d) Dissection of the specimen piece for elongation tests.

e) Lacquer treatment (adherent, brittle varnish)[8].

The modes of testing classified under a, b, c, and e can be regarded as non-destructive. whilst in d the test piece becomes unserviceable. Test c is as yet undeveloped and e is only applicable to such places as are not greatly heated.

We have ourselves used test a, which is simple and does not require great experience in taking measurements.

None of these tests may be deemed perfect. All have the disadvantage that no reliable conclusion can be drawn as to the permanent residual internal shrinkage stress of a bar. Even in the case of dissecting a test piece, it is probable that in spite of thorough precautions the magnitude of the internal stress cannot be determined with certainty. The measurement method therefore remains limited to the determination of the amount of deformations on the surface of a test piece. For practical purposes, however, it has nevertheless to be considered as giving valuable information.

For the measurement of shrinkage stresses an extensometer must be chosen which, unlike the usual extensometer, does not rest on the structure while deformation takes place, but is attached to the surface to be measured before and after deformation.

The application of the extensometer to the structure during deformation of the latter is as a rule out of the question because the time involved would be too long and the pointer of the extensometer deranged by heat, blows or the carelessness of the welders, besides which the instrument itself might be damaged.

The condition that the extensometer should not rest on the structure during welding is fulfilled in the Meyer extensometer (Fig. 2).

Measuring with this type of extensometer has the advantage that for the measurement of all marked places only one measuring apparatus is necessary.

The measuring procedure is as follows (see Fig. 3): — The measured length is determined by the points 1) which are fixed into two countersunk holes provided in the member. The extensometer, which consists of two bars 3) and 4)

[6] *Müllenhof:* Inherent stresses in welded joints. Elektroschweißung, N° 6, 1935.

[7] Röntgenographische Feinuntersuchungen an Brückentragwerken. Schweiz. Bauzeitung,

[8] *Portevin's* Method. Genie civil 8/II/34, and Maybach Motor Factory, Friedrichshafen. 12/I/35. (X-ray examination of bridge girders).

sliding in one another, is placed before and after deformation with its points 1) in the holes of the member. After the points have been placed in the holes, the bars are made fast by means of the screw 5) and the distance between the measuring jaws 6) is measured with a micrometer. After a little practice,

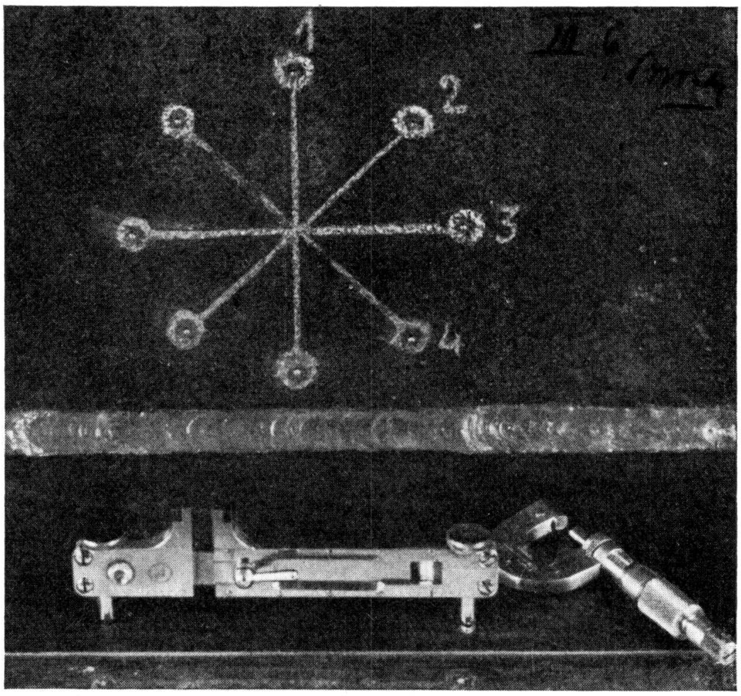

Fig. 2.

Extensometer system Meyer.

measurements to within $\pm$ 1 to 2 thousandths of a millimeter can be made. To avoid errors in testing, the use of graduated dials was purposely abandoned. For the testing of the extensometer a gauge bar is used. The small borings can be kept in condition in a simple way and for a long period by greasing them well and covering them with adhesive tape.

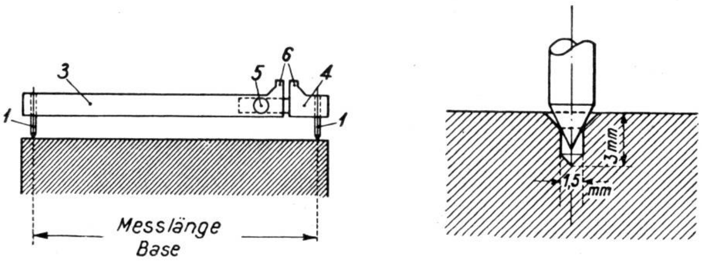

Fig. 3.

Details for taking measurements with the extensometer.

II. Measurements Carried Out.

1) Welding Plates on to Rolled Girders.

Two heavy girders N° 100 DIN carrying the plain concrete decking of the 20 m span underbridge of the Rue Voltaire in Geneva and in each of which the bottom flange had to be strengthened by a 260 × 20 mm plate were measured at different places for deformations. The test was carried out in 1929.

It was revealed that the top flange not directly influenced by the welding was stressed at five sections to ± 90 kg/cm². From this it was deduced that a force of about 70 tons must be exerted along both the welded joints, i. e. in consequence of the heat developed in carrying out the fillet weld and the subsequent shrinkage, the weld and neighbouring material was so shortened that between this disturbed and the upper undisturbed zone a disturbing force of 35 tons was set up at each weld. (Fig. 4.)

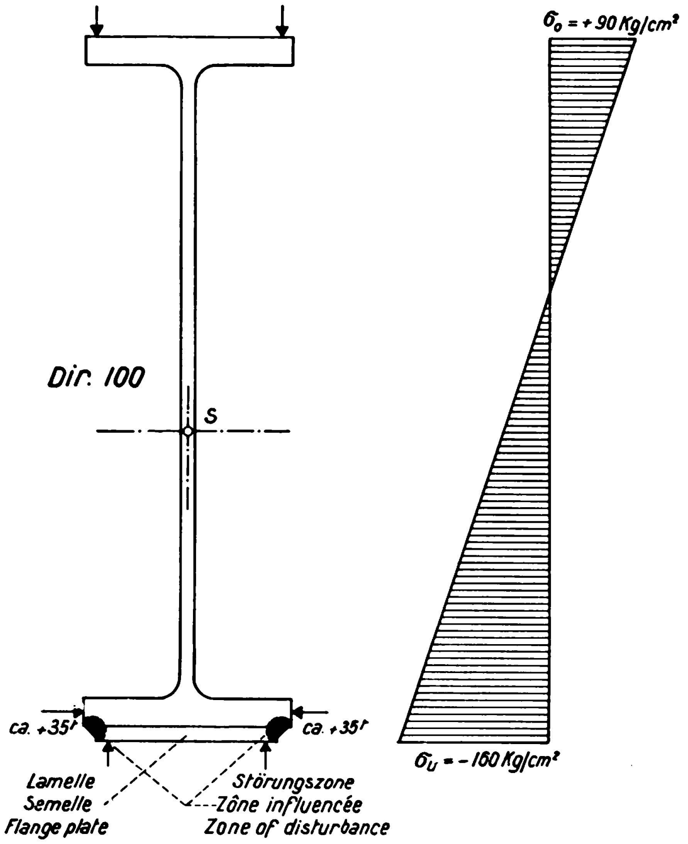

Fig. 4.

Zones of deterioration on girders of the overbridge over Rue Voltaire in Geneva.

It is clear that in this way the disturbed zone is subjected to very high tensile stress and therefore easily broken during fatigue tests. This may cause the premature breakdown of the whole girder.

The expansion measurements in the neighbourhood of the fillet welds revealed average compression stresses of 160 kg/cm², which likewise approximated to a disturbing force of 2 × 35 tons. It is, however, not quite certain whether the measurements taken in the case of the fillet welds do not already fall in the disturbed zone itself, whereby the values for compression stresses recorded would have to be considered as too small[9].

[9] *Bierett:* Tests for the determination of shrinkage stresses in butt welded connections. Paper read before the special committee for welding technique. V. D. I. 1934.

Measurements with thermo-elements at the girders and plates when carrying out the first pass of the fillet weld indicate the temperature gradient shown in Fig. 5, from which the intense local heat action is to be seen.

.2) Manufacture of a Plate Girder Railway Bridge.

When the first welded plate girder railway bridge was being erected on the Beinwil-Reinach line in 1934, several measurements were carried out in the workshop to ascertain the shrinkage stresses. In different sections the deformations were determined after the execution of the fillet welds (Fig. 6).

It can be deduced from the measurements that the disturbing force may have a magnitude of from 30 to 40 tons, since the extreme fibre stress of the flange plates (-350×45) and (-350×30) allow the assumption of a range of mean stress of from 200 to 450 kg/cm². In the web plate no uniform distri-

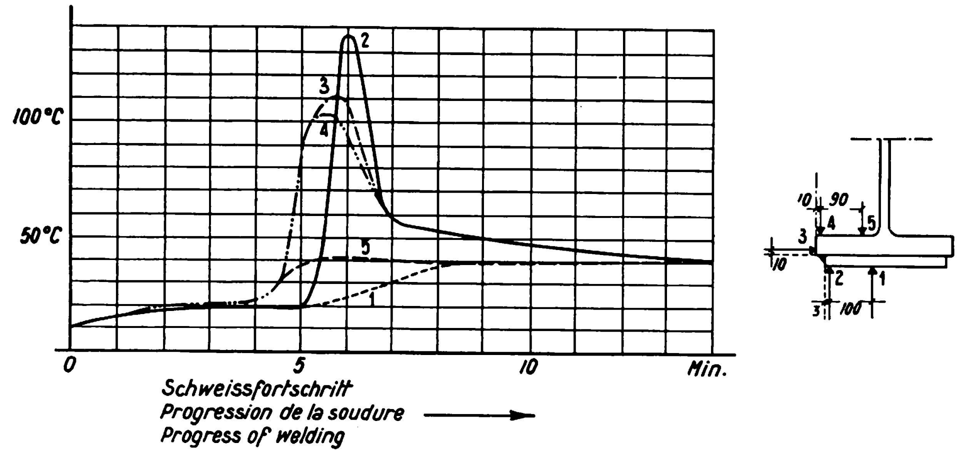

Fig. 5.

Measurements taken with Thermo-elements on the girders of overbridge over Rue Voltaire in Geneva.

bution of the deformations could be determined. This is in a measure accounted for in that the flow of heat in welding is chiefly restricted to the flange plates and only a small part is transferred to the web. Apart from this reason, the relatively thin web plate is easily distorted by considerable bending. Nevertheless, this sets up, where no influence is exerted by welding in other places, distinctly high local compressive stresses (up to 1700 kg/cm²). Measurements indicate a shortening throughout the girder of about. .022 cm/m, which corresponds to a stress of $\cdot \frac{022}{100} \times 2150000 = 430$ kg/cm². In a signal-cabin bridge a shrinkage ratio of even $1^0/_{00}$ could be determined, which corresponds to a mean girder stress of 2150 kg/cm².

In the disturbed zone the tensile stresses set up to maintain equilibrium with the compressive stresses are naturally raised to a high value. If this zone is estimated at about 20 to 25 cm², then the welded joint and the surrounding material is stressed up to and above the elastic limit. In the case of welded joints enclosed on many sides by undisturbed material, the danger of fracturing in the disturbed zone during fatigue tests may be less than in the case of edge fillet welds. It is to this, too, that the good behaviour of welded girders of the foregoing type under fatigue tests is attributable.

3) Strengthening a Puddled-Iron Lattice Bridge.

While engaged on strengthening a number of similarly built puddled-iron bridges on the Brunig route (Lucerne-Interlaken) in 1934 (Fig. 7) we set ourselves the task of determining approximately how welding affected the existing members of the structure. For this purpose measurements taken at

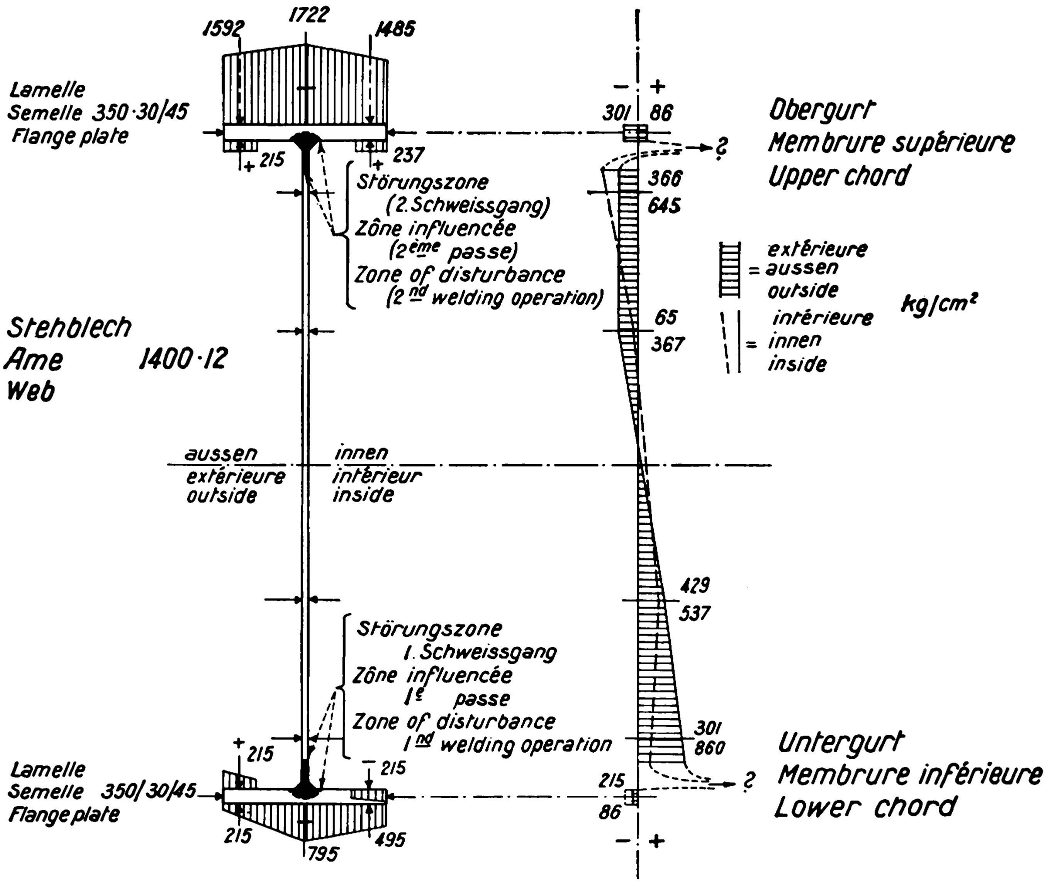

Fig. 6.

Measurements of shrinkage stresses taken on a plate girder bridge on the Beinwil-Reinach Rly-line (results of one section).

particular spots were repeated five months after welding to ascertain whether the frequently predicted equalisation of the disturbing forces is realised under traffic.

First of all, to investigate the shrinkage stresses caused by the welding on of strengthening pieces, measurements for these stresses were taken at the upper chord, bottom chord and cross bracings of three bays and at two posts. At the end of each of these bars three or four measuring places were established, distributed over the old cross section.

Measurements were not carried out at the new strengthening pieces, it being considered that these additional pieces are submitted to high stresses when being fitted, which could not be eliminated. It has nevertheless turned out that it would have been a fruitful source of information if such measurements on the added material had been referred to.

The measurements (Fig. 7) indicate that in consequence of the shortening of the bars due to welding and through the statically indeterminate arrangement of the lattice work, also those bars were stressed which were not welded. The average stress at the centre of gravity determined from both end sections amounted to: —

		Measurements 1st.	Measurements 2nd.*	
Top chord . .	0—I	— 47	—113	non-strengthened members
Bottom chord .	0—1	— 40	— 75	
Tie bar . . .	0—1	+ 84	+133	
Tie bar . . .	II—3	+221	+265	
Post	1—I	—304	—250	
Post	2—II	—461	—380	

In the case of the unstrengthened members (as also for the strengthened ones) the stress curves are extremely involved. According to the diagrams the chord members and the posts are under compressions and the tie bars are subjected to tension. The highest extreme fibre stress of the bars was 840 kg/cm^2.

In the case of the strengthened members of the structure the distorting forces from the deformations cannot be calculated with any degree of accuracy. The measurements show, however, that also in these bars considerable shrinkage and bending stresses were produced. The average stresses at centre of gravity amount to about (mean of the two end sections): —

			Measurements 1st.	Measurements 2nd.*	
	Top chord . .	II - III	—127	— 82	strengthened members
	Top chord . .	VI—V	—300	—162	
	Bottom chord .	2—3	—165	—220	
	Bottom chord .	4—5	—152	—150	
Estimated values	Compression member . .	0—I	—400	—400	
	do. . .	2—III	—500	— 500	
	do. . .	4 - V	—500	—500	
	Bar with alternating stress	IV—5	—600	—600	

After being five months in service, the deformations were re-measured (* second measurement). That alterations had taken place is rendered evident both by the decreases and the increases in the stresses.

A rule cannot be deduced from the figures obtained. It would seem to be too premature to express hopes that in the course of time an equalisation of stresses in the disturbed zones may take place.

4) Manufacture of a Curved, Plate Girder Railway Bridge.

In the year 1936 a plate girder bridge of 27 m skew span of welded construction was installed at Baden-Oberstadt in which the sleepers rest directly on the web plated main girders. The bridge was calculated as a three-dimensional structure under consideration of the skew, on which account the top and bottom wind bracings had to be extremely strong. At the pointed ends of the superstructure negative bearing reactions occurred, so that anchorages were necessary.

In one bay of a main girder centre marks were arranged, and after the welding of the fillet joints between flanges and web plate, the deformation of the web plate and some elongations at the web and flange plates were measured (Figs. 8 and 9). The results were as follows: —

In both flanges compressive stresses were set up and these were actually less in the first welded bottom flange. They averaged 325 kg/cm², being relieved by

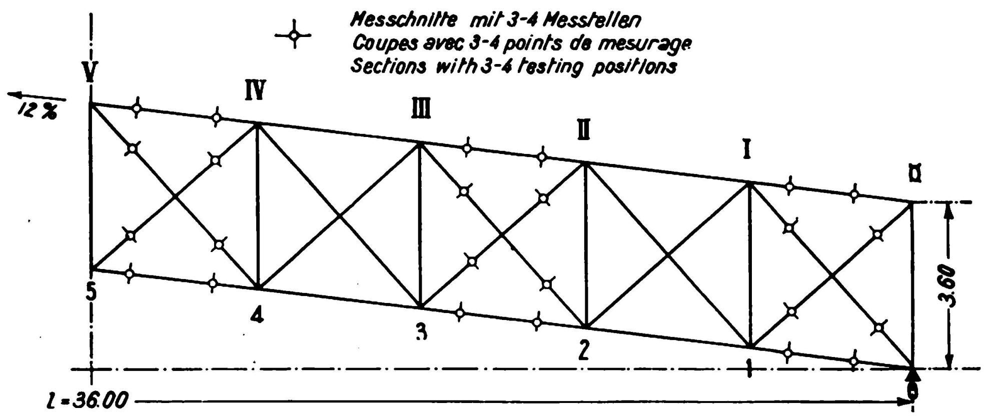

Fig. 7.

Line-diagram and positions of measurements of a puddle iron bridge on the Brünig-line.

the welding on of the top flange. The latter sustained an average stress of about 675 kg/cm².

The web plate likewise indicated unexpectedly high stresses ranging up to 950 kg/cm².

The welding of the flange plates to the web evolved very bad results. At first the gusset plates for wind bracings were welded to the flange plates and after this followed the welding of the flange plate to the web plate. As the wind bracings were riveted, the gusset connections were correspondingly drilled. A close examination showed that some of these gussets revealed cracks which passed through the holes. The deformation measurements taken revealed a distinct eccentric action on the gusset plates, accompanied by considerable tensile stresses.

As regards the deformations of web plate, they turned out to be considerable, which is not surprising in view of the stresses mentioned. The greatest deviation amounted to 2.9 mm near the first welded bottom flange. In this condition the other edge of the web plate was only partly held in position by spot welds.

The shrinkage stresses in the flange in this case were also high, because not only one welded joint, but three, are provided at each flange, bringing into play three disturbance zones, which set up tensile forces (due to shrinkage) and at the same time introduced considerable compression in the girder.

5) Views on Comprehensive Measurements.

From the none too favourable results of the foregoing, briefly discussed measurements, there can be no doubt that for a clear conception of the heat

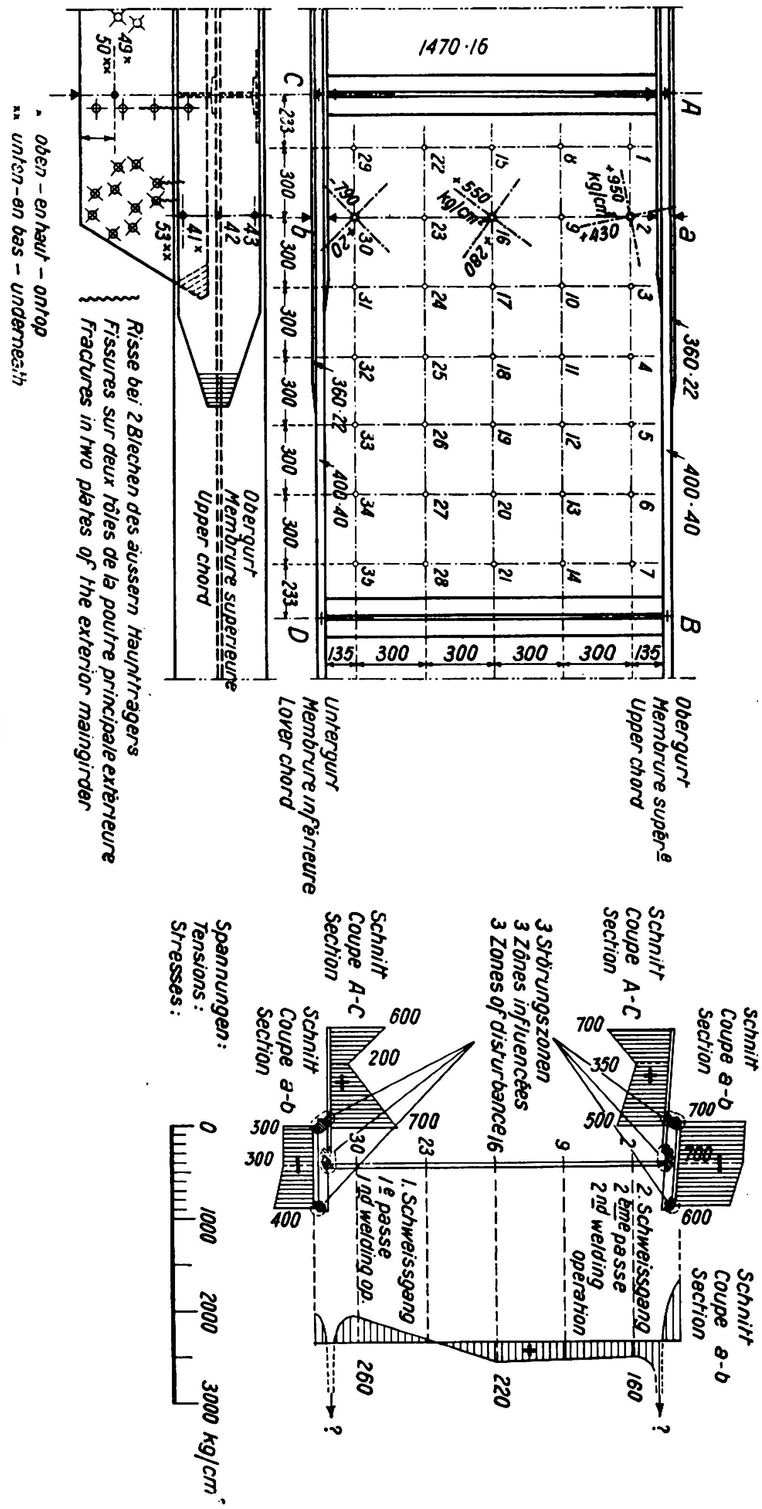

Fig. 8.

Location of measuring positions and stress diagrams for an intermediate girder.

question and also of shrinkage stresses, much more should be done than hitherto. The stresses produced by welding are extremely high and can under certain conditions of dynamically highly stressed structures, endanger the safety of a structure.

For the design of welded structures it is of great importance to possess reliable, exact results of systematic measurements of the heat and shrinkage stresses of different sections, girders and the like, so that even when designing an idea can be formed of the additional stresses set up by welding. It would be most practicable to examine in the first place the deformations of unevenly heated or undercooled flat irons as data for testing the action upon such bars of various-sized welding joints placed symmetrically and unsymmetrically.

In conjunction with this would come the examination of flat bars of various cross sections and connected by longitudinal welds; finally, built-up sections

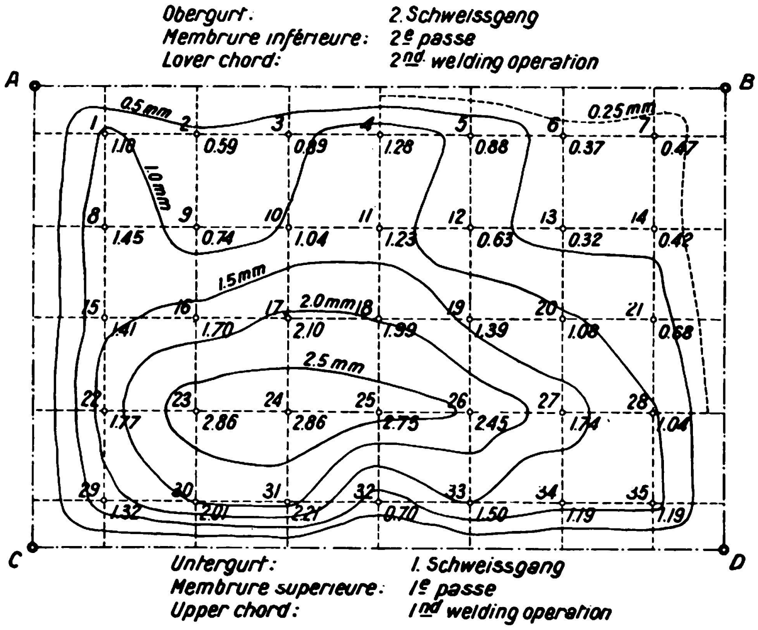

Fig. 9.

Shrinkage stresses as developed by the fabrication of curved plate girder rly-bridge. Deformation of web plate (curves of iso-flexure).

such as girders, and bars with and without stiffeners, should be examined. The greatest attention should be devoted to the exact determination of the zones of disturbances.

In my opinion, extremely valuable results could thus be obtained which would test contradictory statements as to whether it is best to weld with thick or thin electrodes, and which procedure must be given preference when welding. Where it is not necessary to render test pieces unserviceable during the test itself, these should subsequently be statically and dynamically tested.

III. Detailing of Welded Structures[10].

1) Statical Strength and Fatigue Strength of the Welded Members of Structures.

It will be well remembered from the introduction and subsequent hotly-debated development in the manufacture of welded structures, that the grade of

[10] Die elektrische Schweißung im schweiz. Stahlbau (Electric welding in structural steelwork in Switzerland). Intern. Congress for structural steelwork, Liege 1930. Ossature métallique, N° 11, 1935.

an electrode should have been the more highly esteemed, the higher the results yielded by the usual tensile tests. At the present time most electrodes, by suitable butt-welding, reach the same ultimate strength as the material of the structure, in the case of static tests, or even more according to the shape of the test piece. It has become more a question of the shape of the test piece, what ultimate strength should be developed.

When the dynamic strength of welded joints was investigated and made known, a more sober attitude was assumed when judging the actual facts. It soon became manifest that not only the weld metal may be an essential factor for ultimate strength, but just as much the arrangement (butt and fillet welds, magnitude and intensity of the disturbance zone), the execution (thin, thick electrodes, pitting), and shape (convex, even or concave welds) of a welded joint. The co-relation of these three points of view is however still too little appreciated. The cause of this may be found in the publications relating to tests in which the above conditions were not given, so that their influence cannot be estimated.

Finally, it is a moot point whether welding wire could not be found whose composition promotes a more favourable transition zone at the weld than hitherto, and would prevent pitting.

In spite of the publication of a large number of test results it is difficult, if not impossible, to give the Wöhler curves for the different stress limits and modes of stressing from which the curves of permissible stresses can be deduced by the well-known 'Goodman' diagram[11]. Moreover, these stress diagrams will differ according to the number of alternations of the load before fracture; the shape of the cross section also exerts an influence in this connection.

Whilst from two to three million alternations in the main girders of large bridges are equivalent to a fairly long period of service, this number is small for the decking members, so that a great deal more should be ascertained in this connection than has hitherto been done. The Material Testing Institutions would find it well worth while to carry out basic tests, systematically and on a common programme, so that the fundamental strength of material could be thoroughly determined. It would not be necessary, in addition to butt-weld tests, to test cross joints as well as side or end fillets on covered joints, as these are not suitable for tension joints and, in practice, should not be used for such purposes. It would be much more desirable to test models of complete members of a structure, i. e. the shapes actually used. For this purpose the test piece should be so dimensioned that the ultimate strength of the material, as required in practice, may be reliably determined (such as tension, compression, shear, bending, torsion, influence of the shape of the cross section). At the same time the quality of the welding work must be exactly determined.

It may here be remarked that an examination of the welds is required, not only as to their use as joints and connections, but also their effect and the influence of their size and shape upon the through members in the case of transmission forces, as for example posts of plate girders, gussets for wind bracing,

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[11] *Dustin:* Considérations sur l'endurance des assemblages soudés, Revue universelle des Mines. December 1935.

and so forth. In the broadest sense of the word, the extremely important factor of form coefficient should be determined[12].

In order to show that, for example, cross joints for the transmission of tension are not bad merely because the weld has not been carried out properly, we have had tests made to prove this point, and in addition tested similarly formed test pieces worked up from solid plate. Whilst the statical tests of the welded pieces turned out to be somewhat worse than in the case of a one-piece test bar, the difference was not apparent in the pulsator machine, which proves that this type of connection is fundamentally unsuitable for service under tension[13]. The same could be shown for corresponding test pieces with covered joints having end and side fillets, as is often specified in regulations for decisive tests.

2) *Type of Welds.*

In order to throw light on the above-mentioned questions, we have for some years been studying the influence of the shape of the weld upon the strength of the connections and bars. To supplement the expositions made in the foregoing paragraphs, we have carried out trials upon the *influence of the position and the shape of fillet welds on structural steel 37 in the case of stiffeners, ribs, etc.*

The programme of testing was decided upon in June 1934. It provided for the examination, using unjointed flats of 15 mm thickness, of the influence of fillet welds and stiffenings as they occur when webs are reinforced, on through members, taking the following three cases of stiffening arrangements and shapes of welds (Fig. 10).

Keeping to the exact shape of weld presented some difficulty. To be able to compare results of tests, some welds hat to be machined. After a few preliminary tests, tension fatigue tests under repeated loading between P and $\frac{P}{2}$ were carried out (surge load tests). — Test reports of April 14th. 1936.

In the fatigue tests in the region of ultimate strength (surge load strength) with repeated loading, the surface cracked by fatigue was 50 to 80%; between P and $\frac{P}{2}$ at most 50%.

From the diagram of the limiting values in the system σ_o/σ_u the ultimate surge load strength revealed in the through bars for about one million repetitions of load: —

Type of weld	I (even)	15 kg/mm²	
	II (concave)	17 kg/mm²	
	III (convex)	13 kg/mm²	(preliminary test)

With the subsequent grinding of type II, the ultimate strength increased somewhat, so that the second value for this shape may be taken. The conclusions from these tests are as follows: —

[12] *Thum:* Zur Frage der Formziffer, Z. V. d. I., 26. 10. 35.

[13] The test reports refer to the legs of the welded fillet. Statical tests 22 to 26 kg/cm²; $\frac{P}{2}$/P 14 kg/mm²; 0/P 10 kg/mm². Test Report 25. 4. 34.

The fatigue fracture constantly originates at the transition between weld metal and parent metal. It proved to be insignificant whether the fillet welds are exactly opposite or are displaced. The shape of the stiffening has no appreciable effect.

As causes of the considerable fall in ultimate strength of through bars are to be mentioned: — deflection of the stress lines, concentration of stresses at the surface where the weld deposit begins, pitting coinciding with the same spots, changes in the internal structure of the metal and, finally, shrinkage stresses.

The fatigue strength of structural steel 37 is considerably influenced by the shape of the superimposed welds. The gradual transition from weld to plate

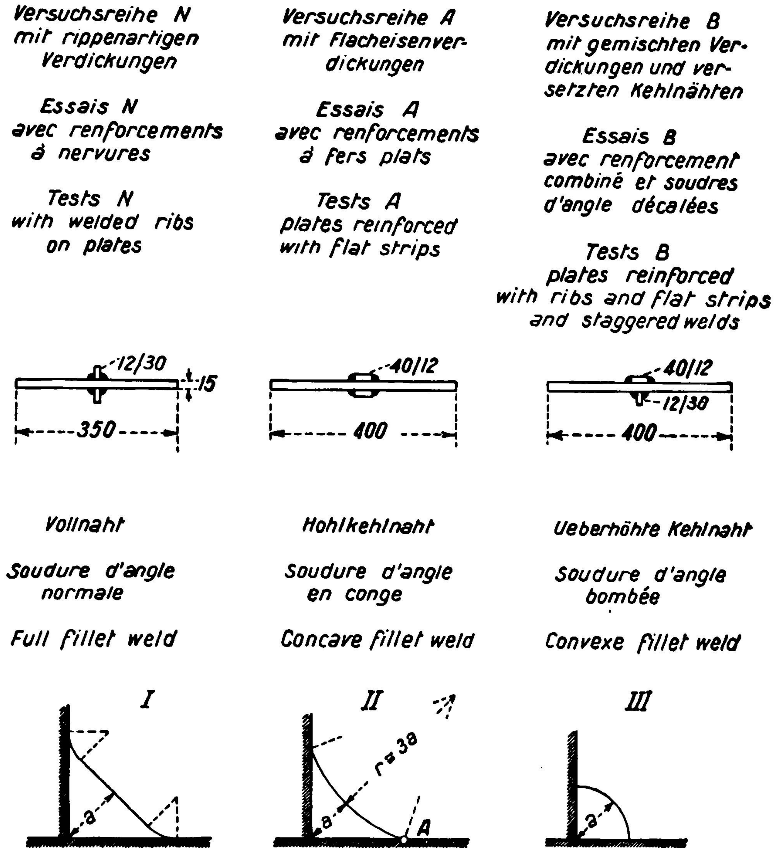

Fig. 10.

Strengthening arrangements and shape of welds applied to un-jointed plates.

causes the least disturbance. By grinding of the transition from weld metal to plate the fatigue strength is further improved. In the case of dynamically stressed members, convex fillets must be unconditionally avoided.

As long as suitable shapes of weld cannot be discovered, it must be taken into account that the surge-load strength of one-piece members subjected to tension is reduced to 15 kg/mm² in the region of superimposed welds, and only reaches .7 to .8 times the value of drilled bars in riveted connections. With a goof form of such welds the surge-load strength may attain that of a good butt weld (16 to 18 kg/mm²). The great influence of a superimposed weld on a member is thus shown and emphasizes the importance of obtaining the form coefficients.

In another series of tests a concave fillet proved to be better than a much thicker convex weld, so that here also the influence of the shape of the fillet is rendered evident. Undercut fillets with 25 to 40% less volume reveal a strength not much below that of the full normal fillet.

3) Application of Welds.

It may now be looked upon as certain that in welded structures the ultimate fatigue strength is considerably lower locally in consequence of the shrinkage stresses, pitting and changes in the texture of the material due to inroad of the weld metal. Additional material thus becomes necessary. It is therefore well to divide the uses of welding into classes in accordance with the importance of the fatigue strength, the classes could correspond to the following range of uses, namely: structural work, road bridges, railway bridges.

Structural works are in general little subjected to dynamic influence, except of course where cranes, machines and suchlike exert oscillations and vibrations. Road bridges are more severely subjected to fatigue, as the effect of lorries is becoming more and more apparent. Next in order come railway bridges, where the rapidity and magnitude of alternating stresses are predominant.

Though in the Swiss Federal Regulations of the year 1935 these differences are overcome by placing the loads and their impact as far as possible on a common basis with regard to the permissible stress, it cannot be overlooked that the period in which the repetition of loads reaches a critical number is not revealed, and that in the highest class, the railway bridges, welding must be most carefully executed and the best welds and shape chosen. It is not admissible deliberately to sacrifice the margin which must be provided for safety on the plea of cheapness and 'common practice'. The ultimate proportions given to a structure afford no proof of the margin of safety. The safety can be completely inadequate without signs of weakness becoming apparent to those concerned.

The space available does not admit of dealing exhaustively with the question of structural details. The author has set out data concerning this question in the publication mentioned at foot[14].

The basic principles to be considered should be somewhat as follows: —

a) To leave no means untried of reducing the welds and diminishing their cross section.

b) Concentration of heat and shrinkage stresses is to be avoided by preventing the convergence of several welds; the welds should be as far as possible surrounded by undisturbed material.

c) Endeavour to arrange for butt welded joints and to place them at positions of slight stresses. A careful selection of materials should make it possible to avoid unfavourable influences on welding by frequent flaws at the surface and edges of rolled sections (splinters, fissures, rolling skins).

[14] Die Schweiß- und Schneideverfahren im Stahlbau auf dem Gebiete des Eisenbahnwesens. (Welding and cutting methods in structural steelwork as applied for railway systems). Chapter on Structures and Bridge-building. Report for the Acetylene Congress, London, 1936.

d) Should a connection have to be made at right angles to the applied force (longitudinal beams to cross girders, cross girders to main girders, wind bracing to flanges, etc.) no abrupt transitions should be left. The corners are to be well rounded off and the welds carefully tooled at the transition to the parent metal.

e) Unwelded sections at the bottom of a weld are to be avoided; instead of fillet welds, K-shaped welds are recommended which admit of a through weld.

f) As with riveting, eccentric connections are to be avoided.

g) The simultaneous use of rivet and weld connections should be avoided, because for this special rules must first be established, especially in view of fatigue.

h) Shrinkage in the case of butt welds amounts to 1 to 2 mm, and in the case of girders in bending with stiffeners ranges up to $1^0/_{00}$.

In the erection of the structure these processes must be carefully supervised so as to eliminate additional coercive stresses.

IV. Manufacture of Welded Structures.

1) General.

In the manufacture of welded structures it is frequently believed that, in comparison with riveting, the procedure is simple and will not involve a difficult change-over either as regards the workers or the workshop appliances. In high-class welding, as required for structures submitted to heavy dynamic stresses, this idea is fallacious. Calculating and designing, marking and fitting, etc., do not as a rule involve less work if the technical procedure is properly carried out. It is further to be emphasized that welded structures should be calculated as three-dimensional, since they do not possess that property of a riveted structure which relieves the load on an endangered member by the yielding of the connecting rivets. However, the best rules should also be adhered to for welding work on which the dynamic stresses are not important, on the one hand with a view to educating the personel, and on the other because of the fact that welding should always be executed with great care on account of its unfavourable contingencies.

2) Supervision of Welding Equipment, Examination of Electrodes.

If a welded structure is to be decided upon, the trouble of inspecting the welding plant of a workshop in which the work is to be undertaken should not be shirked. For this purpose an electrical engineer should be detailed who is acquainted with the functions and capacity of the welding apparatus (conductors, cables, transformers, earths, switches) under different loadings. It is important for the welder to have at his disposal, safely and conveniently, the right current strength, so that he can maintain the welding wire sufficiently and uniformly molten. It would appear practicable only to engage such workshops for important welding work whose electrical appliances withstand a severe test and afford proof that their welding apparatus is maintained in perfect working order.

Further it is important that the respective workshop possesses the necessary cranes and tipping devices for the structural parts so that the welds can always be effected in the most favourable positions and the best forms obtained.

At the site, overhead welding is to be restricted as much as possible to the closing of V-shaped welds.

A further step towards securing skilful welding work is the *inspection of electrodes and welding wire when purchased.* It can of course be asserted that welding wire may be looked upon as mass production and uniformity therefore guaranteed. Yet mistakes are always possible, and on this account a point should be made of inspecting the welding wire when it is supplied, i. e. of testing the exactness of its dimensions and covering and to examine it as regards quality and technical properties. Delivery should only be accepted when the material has stood the tests.

A complete examination should be made of, say, every 10,000 electrodes or a corresponding length of welding wire. In workshops where various types of weld wire are used great care has always to be taken that the prescribed makes are used in every case. Only efficient and orderly workshop administration can guarantee satisfaction in this respect.

3) Examination of Welders.

A great deal has already been written on the testing of welders. We are of opinion that it is not much use putting them through a few of the usual practical tests. However, these tests have to be carried through both for formal and for practical reasons. For, in the first place, a certain standard of workmanship must be attained by the welder, and secondly they are likely to be impressed by the incentive of having to pass tests or execute difficult pieces of work on trial. The quality of the welding work would also be favourably influenced if the welders were given detailed instructions and explanations, both before and during execution of the job, by an experienced specialist who would also have to supervise their work. Often not even the most rudimentary instructions are given to the welders. More should be done than hitherto as regards the theoretical and practical training of the workmen. The institution of a training school for welders would be an excellent means of ensuring a supply of good, reliable craftsmen.

4) Examination of the Welded Work.

As regards the examination of welded work, the best and most dependable method known is that of X-ray photography. The other methods, such as the electro-magnetic and acoustic, are unreliable. Boring and cutting out test pieces only yields local results without permitting conclusions to be drawn as to the average quality of the work as a whole. A combination of the X-ray and cutting out methods gives the best results. This system, however, involves a good deal of time and expense, and the mending of the holes bored may cause very severe additional stresses. For butt welds the use of X-rays yields very satisfactory results in the hands of an experienced operator. Fillet and other forms of weld reveal difficulties in photographing because the thickness of the steel varies considerably as a rule. And finally the great drawback of the X-ray method alone lies in the fact that as yet no generally recognised relationship has been ascertained between the X-ray photograph and the strength of the weld[15]. Thus, at present the only advantage that can be attributed to X-ray photographs is their instructive influence on the welder, as the worst errors are indicated without cutting into the welded seam — a fact that is conducive to careful workmanship. Unfortunately, the X-ray method is expensive and on that account a complete X-raying of all welds is impracticable, at any rate in structural steel-work as we know it today[16].

So welding remains in the truest sense of the word a work in which the reliability of the welder counts for everything. No pressure should therefore be brought to bear on welders doing important work with a view to speeding up its execution. So-called piece-work should be dispensed with. In the case of structures subjected to considerable dynamic stress, the greatest importance should be placed upon the thorough execution of the roots of a weld, which makes it necessary carefully to open and clean roots that are first welded on one side. It is absolutely essential to examine and pass the work at these individual stages. The detection of cracks, flaws and discrepancies in the finished weld is greatly facilitated by the sand blast. This method of cleaning is to be recommended.

V. Summary.

1) In the foregoing report, after a short introduction on the nature of heat and shrinkage stresses, a device for their measurement is described. In conjunction herewith, reference is made to the influence and importance of the disturbed zones caused by welding, which can lead to fracture from static loading or premature fatigue. Further, the results of measurements taken on four structures are cited.

2) The measurements show that the heat stresses and the shrinkage stresses arising from them are extremely important. The precautions to be taken against them consist in the diminution of the cross section of the welds and the avoidance of converging welds.

3) The disturbed zones set up by welding and their reaction on the members of a structure are insufficiently investigated. Systematic examinations are urgently desirable of the disturbed zones themselves and the influence upon them of the type of current, composition of the electrodes, diameter of the electrodes (current intensity) and the cross sections of the structural members.

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[15] A special test with K-welds revealed an ultimate surge-load strength of
14—16 kg/mm² for careful workmanship,
12—14 kg/mm² for good workmanship,
9—11 kg/mm² for bad workmanship.
In comparing X-ray photos these graduations are clearly recognised but not in an absolutely convincing manner.

[16] Eng. *N. Record*, 15. 11. 34. In building the power-house at the Boulder Dam all welds were illuminated and X-rayed in the 45 000 ton pressure pipes (length of weld about 120 km). The results were assessed on the basis of the A. S. M. E. boiler code radiographs.

The Engineer, 19. 4. 35. *Pullin:* Radiography in the Welding Art.

4) There seems little prospect that the shrinkage stresses, as is often asserted, will vanish in time through the action of the working load, unless an otherwise undesirable condition of overstressing should arise, which may result in disquieting deformations or even cracks.

5) The art of specialising the forms of welded structures lies in the most practical realisation of the ultimate fatigue strength of steel, i. e. in the choice of suitable welds and structural details, so that the effect of pitting as well as abrupt transitions are avoided. Disturbance zones should not lie on the most stressed fibres and should be surrounded by undisturbed material. The need for keeping to a definite form of weld makes it desirable under certain circumstances to grind the weld. The smooth welds thus obtained are in any case necessary for durable painting and simple maintenance, as well as for the purpose of recognising cracks.

6) One cannot be too cautious when manufacturing welded structures; the idea that the old, traditional riveting can be replaced by *cheap* welding, is untenable. Welding, being a far more complicated process than riveting, necessitates, if it is to be successful, constant supervision both in the workshop and at site. This testing takes time, and may require the cooperation of trained specialists. For exact work marking of the weld cannot be avoided.

7) But there is more to be done besides testing welders and there work. Care must be taken that working conditions prevail that in themselves are conducive to perfect workmanship. For instance, the electrodes, the whole welding outfit and the welder's equipment must be examined and passed. The importance of the welders' work must be impressed upon them; they must be under the constant control and supervision of an expert.

8) Only when these conditions are fulfilled will it be possible to appreciate undisturbed the great advantages offered by welded structures. It may be hoped that these remarks will act as an incentive towards examining once more all questions to which the introduction of welding has given rise.

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IIIb3

Controlling the Effects of Shrinkage.

Zur Beherrschung der Schrumpfwirkungen.

La lutte contre les effets de retrait.

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The practice prevailing in structural workshops when carrying out riveted constructions used to be that of merely subjecting the rivet material to a heat treatment; however, when welding methods began to be applied, a fusion process was introduced into the workshops concerned. Quite apart from the usual difficulties which beset every metallurgical process, conditions in this case are particularly difficult because small quantities of liquid material at very high temperatures have to be melted to form part of a much larger mass of cold material.

1) Demands made on the Material being used.

This local melting down of one material so that it may form part of other material requires conditions entailing very marked differences of temperature and an equal lack of uniformity with regard to conditions governing expansion and cooling. This lack of uniformity in changes of temperature is the cause of those phenomena which in welding technique go by the name of shrinkage or contraction effects.

The speed at which cooling proceeds depends on a number of different factors, namely: the welding method employed, e. g. — electric arc welding. resistance welding, Arcatom-welding or gas fusion welding. In the case of electric arc welding, the speed depends on the electrode used, which may be plain or covered; it also depends on the working conditions prevailing and the methods applied. These differences are sometimes very great and where circumstances are very unfavourable they may induce effects which resemble those set up after quenching. Very abrupt changes in cooling speed play an important part when the materials being welded are such as show signs of hardening or develop brittleness if cooling is proceeding too rapidly.

These effects are sometimes observed when steel having a high content of carbon is used and also with steel alloyed with elements having an excess percentage of hardening properties, elements such as manganese or chromium, and this is the case more especially when cooling proceeds fairly quickly.

The weld metal while cooling undergoes certain changes. The austenite which is present after solidification undergoes various changes of texture, passing from martensite, troostite, and sorbite, until finally it is found in the form of stable perlite = or ferrite-cementite. When cooling proceeds slowly, the changes referred to above take place in the regions of high temperature in which no stresses are set up as a result of the changes of volume consequent upon the physical changes.

Where additions of carbon or alloy exceed a certain amount, these phenomena of physical transformation may induce corresponding stresses resulting from the changes, because when cooling is rapid the changes of form settle in the lower zones of temperature in which more marked resistance of form to changes of volume is observed and in which, furthermore, the thermal tensions reach very high figures. Another possibility is that the change from austenite ⟶ perlite, desirable when using ordinary structural steels, does not occur when certain alloys are added, nor when cooling is effected very suddenly, but that in certain circumstances the structure of the metal in the weld-zones will finally be of an intermediate composition; where circumstances are most unfavourable, a hard and brittle martensite will be produced.

Experience has taught us that a mild unalloyed steel with a low carbon content, such as is used in steel structural engineering, does not set up any of these undesirable phenomena. When using steel containing little alloy, this problem may possibly become more serious. In order to avoid deleterious effects, the bending test with metal in the tempered state should be carried out; to this end the steel at 900° C. is quenched in oil at indoor temperature after which it should be possible to bend the steel round a mandril having twice the thickness of the metal plate. This last operation is also carried out at indoor temperature.

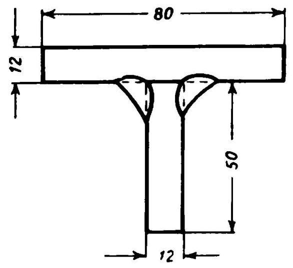
Steels which are to be welded may have only a moderate content of impure ferrous matter, such as sulphur and phosphorus. Sulphur is known to cause "hot brittle" fracture; if the sulphur content is too high there will be some danger of cracks occurring before the metal cools. Phosphorus sometimes causes "cold short" fracture; steel containing too much phosphorus tends to give the structure a coarse grain which results finally in small cracks appearing in the neighbourhood of the welded joint.

Sufficient margin for the change of form of the weld metal when cooling does not necessarily guarantee immunity against cracking. It is highly probable that most cracks start while the temperature is still high. (Section 6.)

When the sections or plates are of increasing thickness, that is, according as the volume and rigidity of the parts to be welded are greater, the risks of cracking also increase. This is probably very largely due to the higher conduction of heat and thus the problem discussed above in connection with steels having high carbon contents may also be significant in the case of structural steels of low carbon content.

It is necessary, therefore, to carry out suitable experiments with a view to eliminating types of weld metals which induce cracks when used for welding basic material of the kind in question. The German State Railways have recently introduced a test for resistance to fracture which is used when approving welding rods and electrodes. (Fig. 1.) I believe I am right in saying that many firms who wish to improve their welding rods carry out similar investigations under even severer conditions, namely, by using heavier metal plates.

Mechanical processes, such as machining, for instance, frequently used to combat shrinkage effects in welded parts (Section 7 b), often require, just as other mechanical processes do, that the weld be machineable, not only in a hot, but also in a cold state, so that welding rods and welding conditions which induce an excess absorption of oxygen and nitrogen may be eliminated.



Fig, 1.

Test to investigate the predisposition of electrodes to cracking.

The fact that shrinkage effects have to be taken into account makes it necessary to eliminate welding rods having excessive exothermal properties, that is, those which melt too easily when subjected to unusually intense heat. The effects of heat can be easily gauged by observing the extent of the tempering zones next to the welded joint. The use of welding rods which are known to extend the zones of heat effect unduly should be definitely prohibited in steel construction.

2) Processes of Expansion and Contraction.

The visible effects of heating, e. g. deformation which becomes apparent in the form of shortening of the metal-bending and buckling, will be dealt with only inasmuch as they help to elucidate the problem of shrinkage stresses and cracks caused by shrinkage or contraction. Control of deformation has been far more extensively developed by industrial enterprise than has investigation of the problem of how to reduce tension and cracking, undoubtedly because deformation is much more striking than are the latter phenomena. Quite frequently the measures taken to prevent undesirable changes of form lead to increased stress and to risks of fracture. For this reason it is sometimes advisable to aim at some adjustment in order to solve the problem of deformation and tension occurrence satisfactorily.

a) Transverse Contraction.

When molten metal in a liquid state is allowed to move unrestrictedly, it has the property of contracting uniformly in all directions. In practice unrestricted contraction in a transverse direction occurs only in the case of butt welds and then only in welds which have been executed fairly rapidly. Unhampered contraction is never possible in a longitudinal direction.

When plates which are to be welded are placed in position for welding without being rigidly fixed, transverse contraction takes place as a consequence of the welding groove becoming narrower under the effect of the heating of the parts to be welded, and also because the filler material which has been used contracts. The first of these two factors is by far the more important. The amount of heat used also influences transverse contraction, and that amount depends on the size of the section of the weld and on the specific heat consumption required to melt the welding rod.

H. Koch[1] and *R. Malisius*[2] have carried out detailed investigations on what takes place when transverse contraction is proceeding in butt welds, and we owe the following data to their work.

Contraction takes place where welding is continuous because the melted weld metal is poured gradually into the joint and thus, instead of spreading evenly over the whole length, it moves forward lineally. Tacking, if properly carried out, will reduce contraction considerably, and where such contraction does occur, its course will be along parallel lines. The welding of a joint in sections may have similar effects if correctly executed, for instance, when using the "step-back" welding procedure; as a rule it will be preferable to reduce contraction by weld-tacking as much as possible.

Contraction increases with increased thickness of the plate, because the central width of the weld is increased. (Fig. 2.) Transverse contraction can be

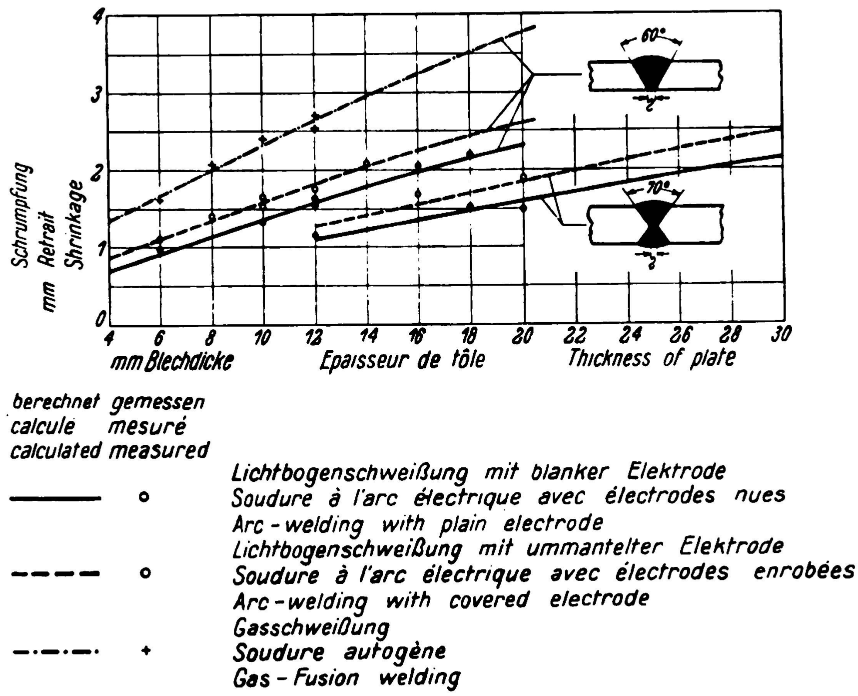


Fig. 2.

Transverse shrinkage of welds of well-tacked joints.

attenuated by considably reducing the cross section of the joint so far as this can be done without prejudice to the weld. (Fig. 3.)

Multi-layer welding, usually applied for heavier plates, sets up an angular contraction alongside the parallel one and this may lead to bending of the metal. The entire contraction in this kind of joint consists of parallel shrinkage and angular shrinkage. (Fig. 4.)

Angular contraction, and also the entire contraction, increases very consid-

[1] *H. Koch:* Contraction and Contraction Stresses in Connection with Electric Arc Welding. Treatise T. H. Hannover, 1935.

[2] *R. Malisius:* Contraction of Butt-welded Joints. Series: Information Concerning the Theory and Practice of Electric Welding (Publ. Vieweg) H. 2 and Electric Welding 7 (1936) Pp. 1 to 9.

erably with increase of the thickness of the plate. The number of passes of weld metal is also of great importance. In Fig. 5 the conditions requisite for V-joints with plates of 12 and 18 mm thickness respectively are seen. In order to prevent an excess of angular contraction and of the entire contraction, it is advisable to keep the layers thin and to use thick welding rods or electrodes in preference to thinner ones. If the number of passes is too limited, the structure

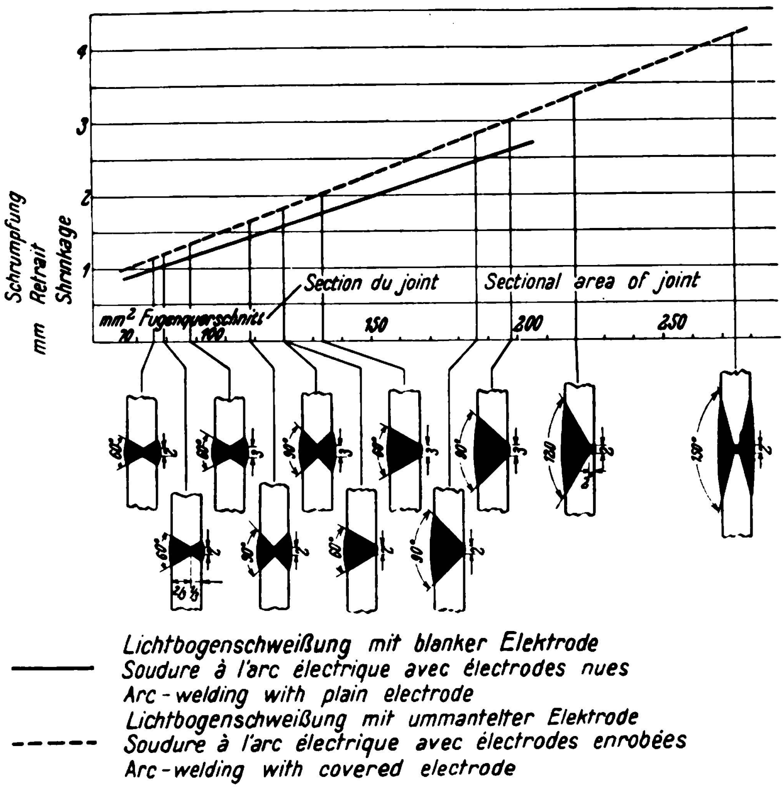


Fig. 3.

Shrinkage of butt welded joints of different shapes (plate thickness 12 mm).

of the metal will be adversely affected and there will be some danger of cracks being formed.

Conditions can be much improved by using symmetrical or quasi-symmetrical joint cross sections, in particular if the weld layers in the upper and lower joints are welded alternately[3].

Transverse contraction and angular contraction play an important part with fillet welds. Both these contractions can be limited, just as in the case of butt welds, by using welding rods which do not require an undue consumption of heat, and provided the weld cross sections are kept as small as is compatible with the production of sound welds. Risks of cracking do, however, occur if the fillet welds or first passes of weld metal are too thin. (Section 6.)

Transverse contraction is less marked in fillet welds[4] than in butt welds

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[3] *E. Höhn:* Welded Joints in Boiler and Container Construction, Pp. 56/59. Published by Springer, 1935.

[4] *Lottmann:* Welding applied to Shipbuilding. German Publ. Strauss Vetter & Co., Berlin, and Electric Welding *1* (1930) Pp. 133/4.

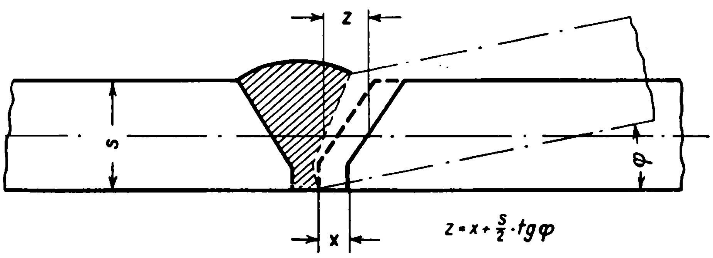


Fig. 4.

x = Parallel transverse shrinkage. φ = Angular shrinkage. z = Total transverse shrinkage.
Component parts of transverse shrinkage.

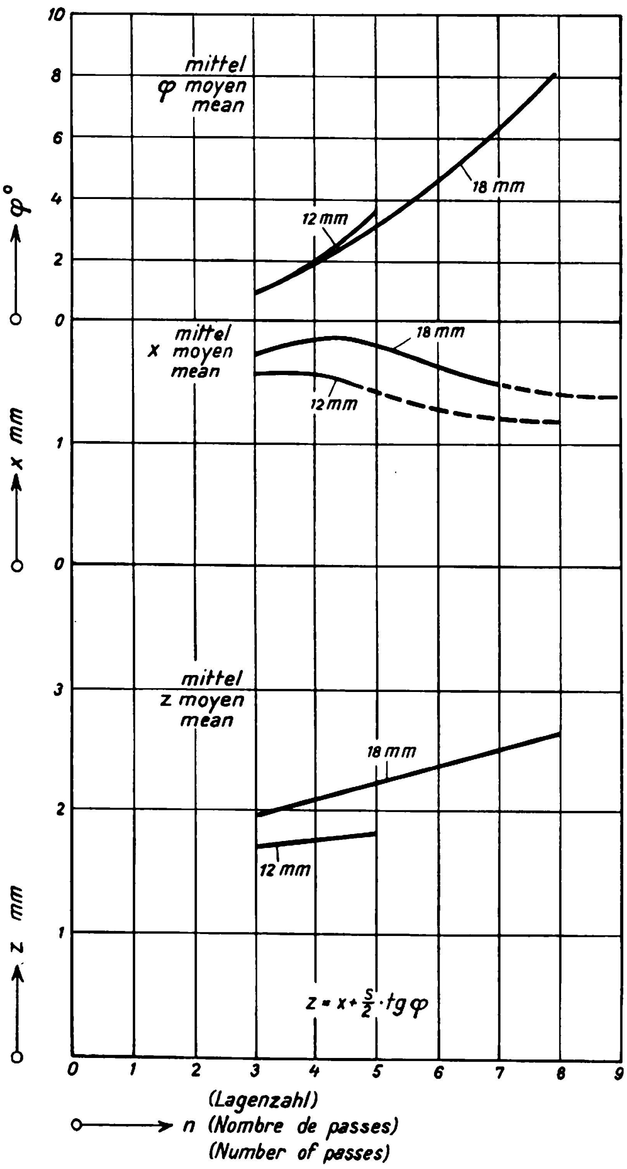


Fig. 5.

Shrinkage in relation to the number of passes for plates of constant thickness (12 and 18 mm) acc. to H, Koch

Constant: l = length of weld 180 mm; b = total width 240 mm; V-shaped weld; v = width of joint 3 mm.

Welding process: arc-welding with alternating current and covered electrodes 4 and 5 mm dia.

Normal amperage; clamped at both ends.

(Fig. 6), as the zone affected by the melting process reacts on a certain part of the thickness of the metal only. When dealing with cross sections of welds which maintain their uniformity, we shall find that the transverse contraction does not depend on the thickness of the metal as in the case of butt welds; it is more likely that there will be less contraction with heavier plates. Contraction depends very largely on the welding road and its diameter, and also on the working methods used. Every enterprise has its own particular manufacturing practices so that tests should preferably be made on the type of joint usually adopted.

b) Longitudinal Contraction.

When depositing the intensely hot molten weld metal into the joint, the neighbouring zones of the latter which are also at a high temperature will expand, but this change of form in the direction of the welded joint can be effected only in connection with the colder parts at the side. The comparatively abrupt drop in temperature which always accompanies welding and the ever

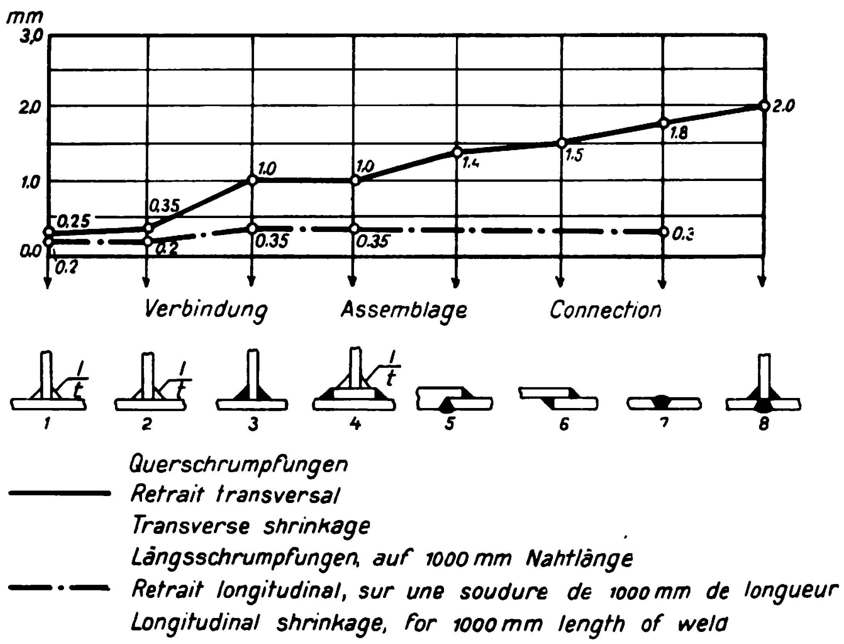


Fig. 6.

Transverse and longitudinal shrinkage of welded connections acc. to Lottmann.

increasing heat coefficient of expansion which is not stable at higher temperatures, induce plastic "upsetting" in the very hot zones and this is the real cause of the longitudinal contraction and contraction stresses which are set up.

When using ordinary carbon steels the ductile limit starts in the neighbourhood of 600 to 700^0 C., after which it rises comparatively quickly as the temperature drops (Fig. 7). The zone of 600^0 C. is surrounded by zones which offer little resistance to deformation and by others with increasing resistance, and this signifies that the maximum of plastic "upsetting" is to be found at this point.

When carrying out electric arc welding, in particular when using polished electrodes, the zone having a temperature above 600^0 C. is a very narrow one, thus the maximum "upsetting" takes place in close proximity to the weld seam. Where the zones subjected to heat are wider, the points of maximum "upsetting" are generally outside the welding zone (Fig. 8). The transition from

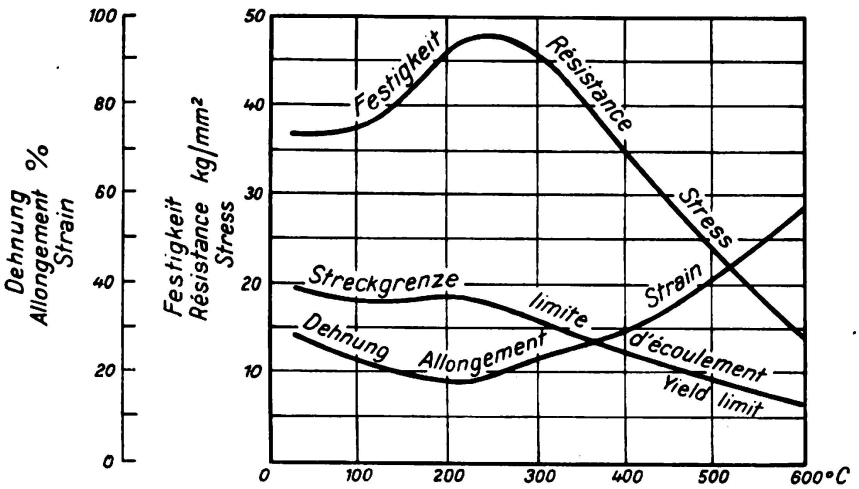


Fig. 7.

Strength properties of non-alloyed steel acc. to G. Urbanczyk.
C = 0,14%; Mn = 0,51%; P = 0,016%; S = 0,032%.

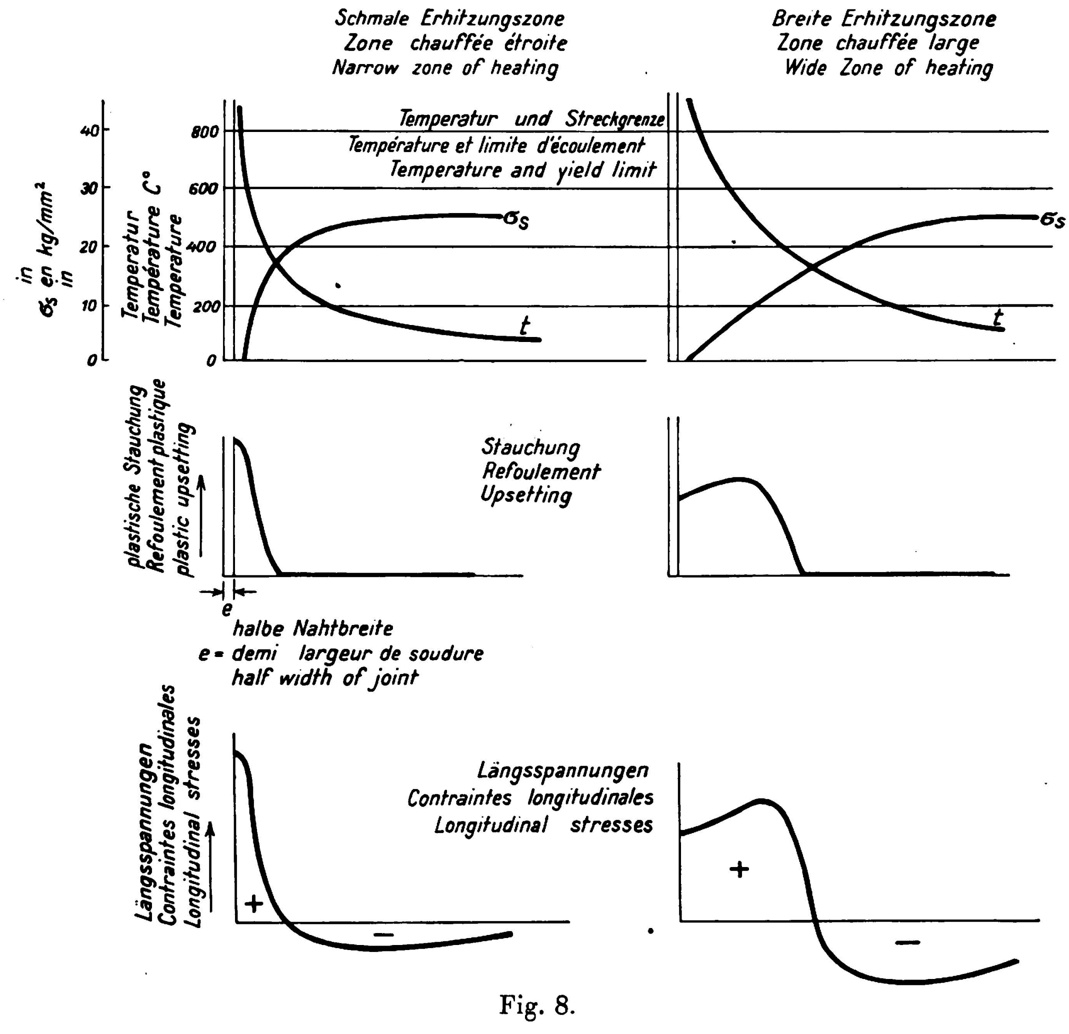


Fig. 8.

Temperature, upsetting and stress conditions for narrow and wide zones of heating.

basic material having low resistance to deformation to that of higher resistance is less abrupt in proportion as the changes in temperature of the larger zones of heat are more gradual. The maximum "upsetting" is therefore lower.

Longitudinal contraction is practically only a fraction of transverse contraction (Fig. 6). Formerly the conclusion frequently drawn was that the remaining shrinkage stresses in the direction of the weld were low, and thus the phenomena of longitudinal contraction stresses were not considered to be very important. This shrinkage stress problem can only be dealt with rationally if, contrary to the above opinion, it is tackled by starting with the longitudinal contraction and its effects.

3) Shrinkage Stresses when for part loosely held in position.

Those parts which have been only slightly heated and those which have suffered elastic deformation only during the process of welding will try, when cooling, to regain their original length, while the welding zones which have been shortened by "upsetting", will try to attain a length which is shorter than their original one. They are prevented from doing this, however, by the connection that exists between them and those parts subjected to elastic deformation only. The result is the setting up of a weld stress in the direction of the weld, with high tensile stress in the weld itself and in those zones of higher temperature and also of corresponding compressive stresses (stresses of reaction) having similar tendencies due to equilibrium in the cold or moderately hot parts of the material.

Where the zones of heat are narrow a high tensile stress is induced which covers a very narrow zone of the welded joint. Where the zones of heating are wider the tensile stresses will be less intense and the highest coefficient will be found beyond the joint, while the zone under tension will be proportionately greater. The compressive stresses of reaction are low in the narrow zones of heating, while where the zones are wider, the compressive stresses and warping will be considerably increased (Fig. 8).

Transverse stresses are set up at the same time as the longitudinal ones. This has been observed in the first place in connection with butt welds; the position as far as fillet welds are concerned is more complicated (Section 5 d). The assumption here is that the transverse contraction is not hampered by clamping of the material or by internal tension (Section 5 a).

If the temperature of the joint is raised, a slight, even if unnoticeable, outward curving of the edges will take place so that the distance at the ends of the joint will be larger than at the centre. While cooling proceeds the bending back action will be more marked under the influence of the longitudinal contraction of the shortened zone of welding. The weld metal which has been run into the joint and which is cooling will be pressed against the ends of the weld joint under these influences, while in the central parts they will be drawn apart (Fig. 9). (The term "non-rigid" in connection with welding or welded parts is thus shown to be antithetical and can be interpreted solely as characterizing external conditions.)

The longitudinal and transverse stresses which are set up have to comply with the conditions imposed by equilibrium (Fig. 10). The state of tension has

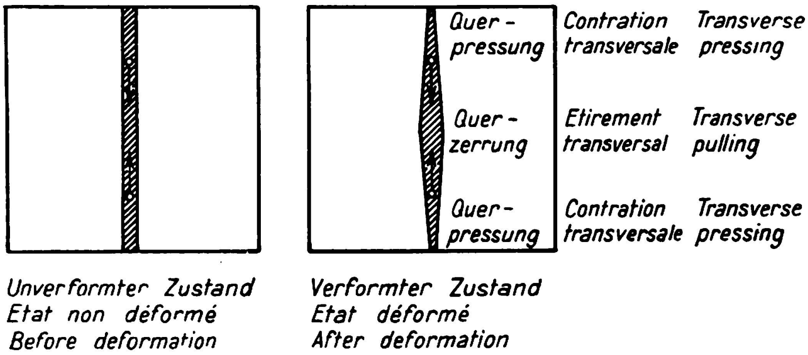
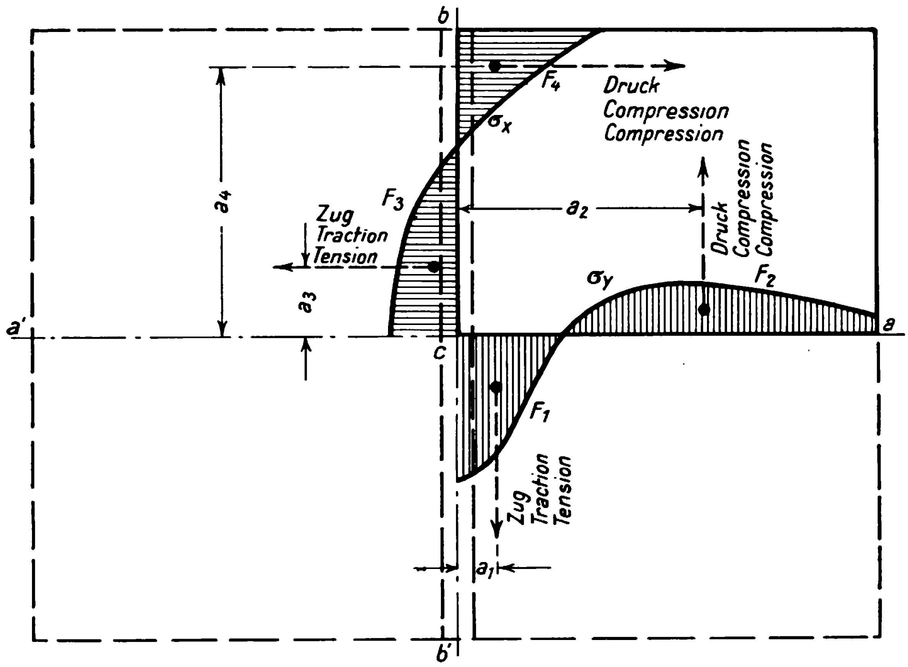


Fig. 9.

Longitudinal shrinkage causing transverse stresses for free welding.



$F_1 = F_2; F_3 = F_4$

$F_1\ a_1 - F_2\ a_2 = F_3 \cdot a_3 - F_4\ a_4$

Fig. 10.

Relation between longitudinal and transverse stresses based on internal equilibrium.

been described by the author as the "natural welding state of tension", because it corresponded to the peculiarity of fusion welding in which connections are made by means of narrow joints filled with weld metal.

In practice it will always be necessary to take certain stresses into account (Section 5). Welding showing no "transverse tension" is possible only when the weld metal is run simultaneously into the whole length and depth of the groove and when resistance welding is the system applied. Nevertheless it is a fact that when a large number of important butt welded joints are made, the influence of transverse contraction is so far lessened that the conditions of "non-rigid" welding constitute the decisive factor. Transverse stresses which are caused solely by longitudinal contraction in the absence of any transverse stress, are indeed so great that they must not pass unnoticed even in cases in which tension is set up on a large scale.

Experimental investigations have confirmed the arrangement of longitudinal and transverse stresses in butt welds as decribed above (Fig. 11, Plate 20, 3 and 15). Even with welds of greater length and thickness and welds consisting of

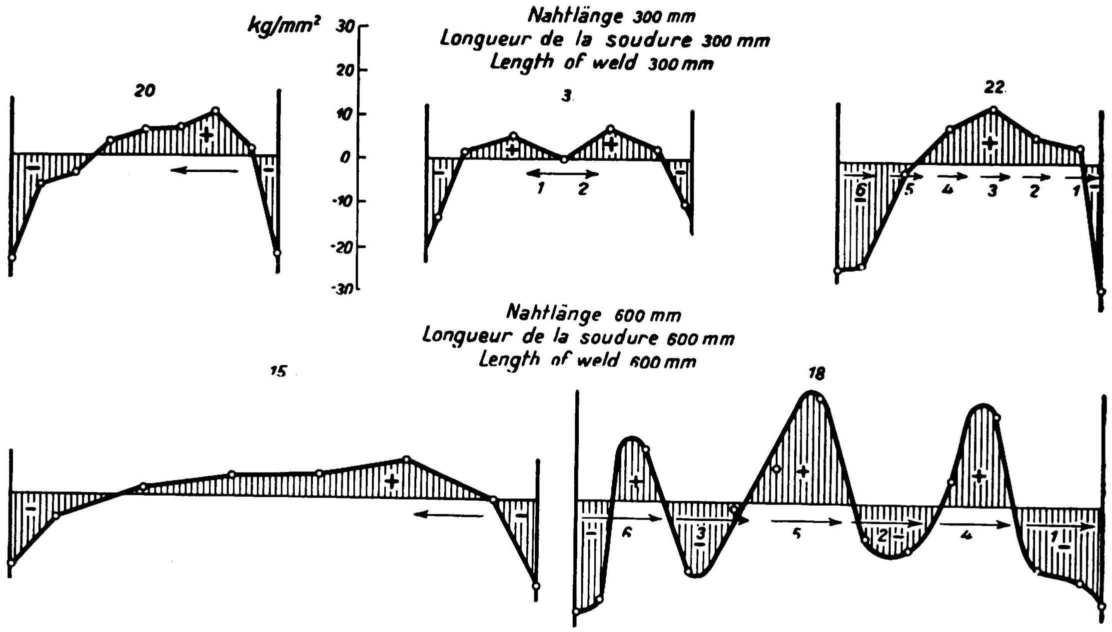


Fig. 11.

Material: St 37. Thickness of plate: 12 mm. Welding process: arc-welding. Welding wires: Böhler "Elite" cored electrodes. Number of layers: 3. Transverse stresses in welds for free welding and different forms of weld stepping.

several layers[5], something similar to this state of stress is observed, so that it is really of great practical importance. The most essential feature is the occurrence of intense compressive stresses at the extremities of the weld, and this offers a certain natural safety factor for the ends.

Experiments have proved that the effects resulting from the transverse stresses due solely to the longitudinal contraction and exerted on the resistance have no bad results provided these stresses alone have been set up.

[5] *G. Bierett:* Experimental Investigation into Shrinkage Stresses in Welded Butt Joints. Publication by Association of German Engineers, 78 (1934) Pp. 709/715.

G. Bierett and *G. Grüning:* Contraction Stresses in Autogenously Welded Members. Aut. Treatm. of Metals. 27 (1934) Pp. 259/266.

G. Grüning: Welding and Shrinkage Stresses. Steel Structural Engineering, 7 (1934), Pp. 110/112. For summaries of these three treatises v. Comm. of German Mat. Testing Inst. Special publication 25, Pp. 65/86.

F. Bollenrath: Autotension in Electric Arc and Gas Fusion Welding. Treatise. Aerodyn. Inst. Techn. College, Aix-la-Chapelle. 1934 H. 14. Pp. 27/54.

F. Bollenrath: Further Investigations on Self-Stresses in Ordinary Welded Joints. Archives of Mining Industry. 9 (1935/36), H. 4. Pp. 203/207.

4) Longitudinal shrinkage stresses.

Longitudinal shrinkage stresses are of particular importance in steel structural engineering for welds which run in the main direction of forces. The cross section of the welding zones constitutes as a rule only a small portion of the entire cross section. The term "welding zone" as used here refers not only to the cross section of the weld itself, but also to that part of it which is at a higher temperature and which has been clenched when in a heated plastic state. Apart from exceptional cases, the entire cross section vertical to the welded joint, as compared to the cross section of the weld-zone, will always be a very large one.

Intense tensile stresses occur in the welding zones, while the rest of the section is mainly under compressive stress. The conditions governing tension in the weld zones themselves are of importance for those parts which when in commission are exposed to tensile stress also, and the compressive stresses (stresses of reaction) set up by the process of welding are important for the other transverse parts which are subjected to compression.

The longitudinal weld stresses reach their maximum where the high temperature zones are narrow and when the weld metal, or the parent metal, is very strong. If the parent metal is of unsatisfactory quality, and particularly if the various parts of the job are massive, there is some risk of cracks forming across the welds. Parent metal or welding rods that give rise to defects of this kind should be eliminated before starting on the work.

The extension of longitudinal weld stresses can be reduced by extending the heating zones. Welding rods which set free large amounts of heat and welding methods or processes having similar effects are favourable from this point of view. This fact should be considered when dealing with members of a structure which are under tensile stress only. Meanwhile it must be remembered that when the heating zone is larger, the resultant power of contraction which influences greater width increases and simultaneously the opposing compressive stresses increase. Therefore when members are under compressive stress only, it is advisable to set up an intense tensile stress in the welded joint affecting a limited zone rather than less intense tensile stresses which, while extending over a larger zone, set up higher compressive stresses. All these effects should be taken into account when selecting the welding rod or electrode. In electric arc welding, this point of view should — for instance, in the case of compressive members — take precedence of other requirements such as deformation capacity. In girder construction it is necessary to avoid excessively narrow zones of heating, at any rate for the longitudinal welds in the tension flange; in the compression flange they should be limited as far as possible. This differentiation in selection is not at present customary in practice; however, full use of all existing possibilities would certainly contribute to improved conditions.

Very little definite evidence is forthcoming regarding the figures for compressive tensions of reaction which might be useful to designers from the point of view of risks of fracture, or to workshops when considering the effects of warping. *Doernen*[6] has laid down the compressive stresses of reaction for the webs of welded I-girders.

It can be deduced from this investigation that the designer should limit the weld cross section to a minimum. On the other hand, in these cases the workshops must limit as far as possible the cross section of the zones of the weld by appropriate measures and these measures should include the use of welding rods which do not set free excessive amounts of heat, and should carefully comply with the regulation cross sections for welds.

Fig. 12 shows the results of measurements of actual tension of welded rolled sections in which visible compressive stresses occur at the edges. Even if it appears in these cases as though the higher actual compressive stresses do not influence stability to any great degree — and the results of bending tests carried out on that type of structural member by the State Material Testing Laboratory at Berlin-Dahlem seem to confirm this — all possible means of the kind referred to above should be applied in order to obtain a really well designed structure.

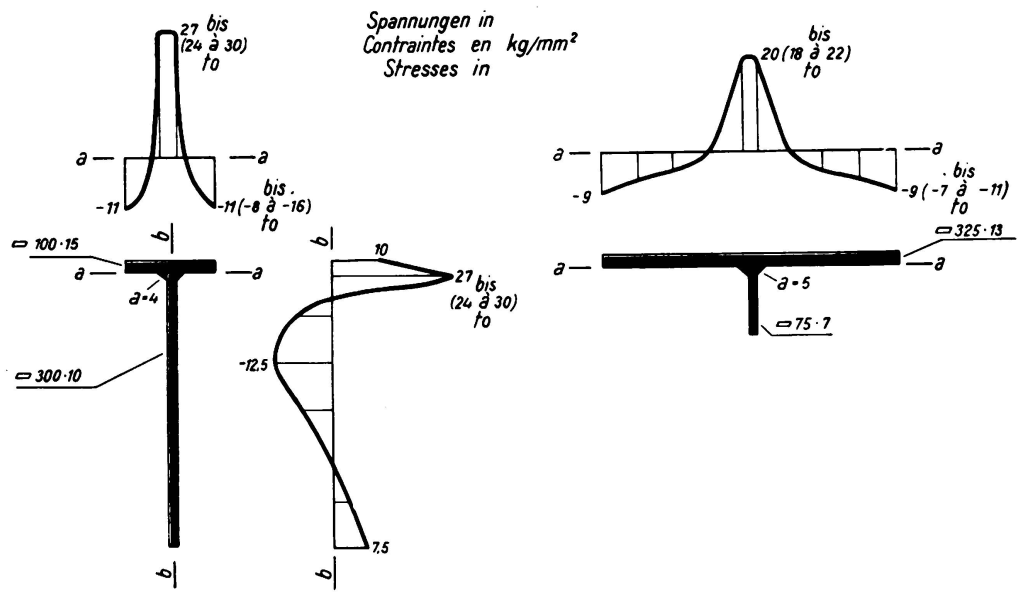


Fig. 12.

Welding stresses along the welds in sections welded with fillet welds.

Electric arc-welding.

Note: The figures in brackets are for extreme values as determined by numerous similar investigations.

5) Transverse Stresses.

a) External and Internal Transverse Stresses.

There may be some transversal obstruction to the process of expansion and contraction

a) due to external rigidity. Such external rigidity in this connection should be taken to mean the clamping or fixing of the parts to be welded

[6] *J. Doernen:* Contraction of Welded Steel Structures. Steel Structural Engineering *6* (1933), Pp. 22/24.

previous to carrying out the welding. Examples of this kind are: web welded joints connecting continuous flange plates or flange plates already welded and flange plates and web joints welded for the purpose of connecting massive structural members;

b) due to internal rigidity or tension. By internal rigidity of a welded joint is meant in the first place the tension existing in those parts which, while not rigidly fixed, are adjacent to the sections or layers of weld which have been terminated and which prevent the possibility of welding the joint along its whole length without setting up transverse stresses. These stresses are induced by the fact that it is not possible to carry out simultaneously the operations of melting, welding, heating and cooling the various sections of the joint and the various runs of weld metal; these operations have to be carried out in rotation.

c) The tensions which arise when fillet welds are made resemble the effects of clamping;

d) As special cases mention might be made of welding patches into the material or the welding of plates on to larger members by means of welds that cover a large portion of the structure. Even where the whole weld is executed in one single operation transverse stresses are set up in this class of work. Circumstances are therefore similar to those observed with external rigidity.

e) External and internal rigidity or tension are often induced simultaneously.

b) Connection between transverse stresses and a) thermal conditions and b) physical thermal properties of the material being used.

Thermal expansion of the heated parts adjacent to the zones of welding leads to "upsetting" of the welding zones in cases where tension exists in the region of higher temperatures. This thermal expansion is increased in proportion as the heating zones are larger. Thus the additional transverse shrinkage stresses depend mainly on the amount of weld metal deposited into the joint and on the specific heat consumption per unit of weld metal that has been melted. The transverse shrinkage stresses seen in Fig. 3 represent a standard by which to measure tension variations for various sizes of weld cross sections; however, the stresses there shown are merely the result of the narrowing of the joint due to the effects of heat and contraction of the melted material flowing into the joint while the differences are still greater in the heated zones owing to "upsetting". When welding, the process of contraction takes place first of all in the welded joint and runs contrary to the expansion of the welded parts owing to the effects of the heat which is escaping. When welding parts that are clamped, this expansion acts in a compressive way on the welding zones. The physical properties of the material being welded influence these processes very considerably; such physical properties are: coefficient of expansion, specific heat, heat conductivity and ductile limit and these are not determinate coefficients but factors which are affected by temperature and therefore elusive when it comes to calculating them. When gauging the effect of these factors, however, it is easy to note that with large supplies of heat conditions will be less favourable than with small ones; experiments and practical experience have confirmed this.

c) Measures for reducing tension effects.

One of the most important conditions underlying the reduction of external and internal stresses and necessary in order to obtain welds exempt from excessive transverse stresses, is that of keeping down the size of the weld cross sections and the elimination of welding rods which require undue specific heat consumption.

The most reliable way of reducing external stresses or anything that resembles it is by elastically shaping the parts adjacent to the joints and by appropriately dealing with each welded seam in turn. This complicated task will be considerably lightened if the edges of the joint are previously slightly bent out of the plane of the plate (where transversal joints are unsymmetrical the bend should be to the side of the widest part of the joint), and this practice should be still more strictly followed when welding plates requiring two parallel joints or when welding plates into or onto parts with joint along the whole circumference. An important example of this class of work is that of a web joint in a universal joint of a girder (Fig. 13). A slightly cylindrical intermediate piece, not too

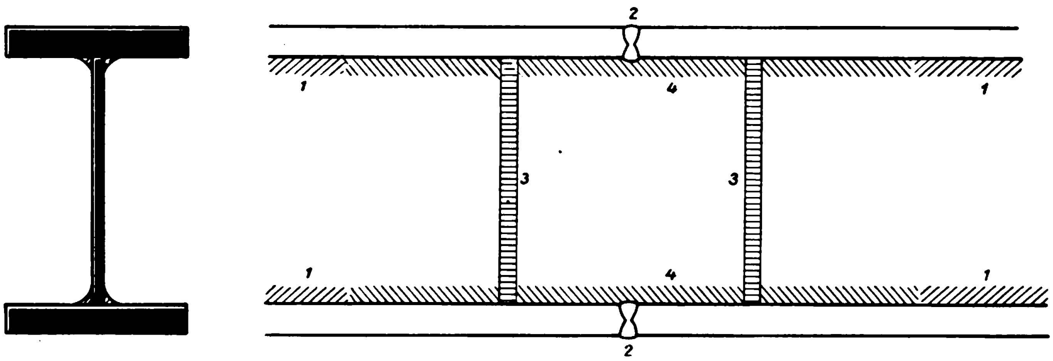


Fig. 13.

Appropriate welding procedure for girder joint.

short, should be used and elastic sections provided in the neighbouring web members by leaving the adjacent collar joints provisionally open; this will facilitate the execution of the web joint even if the joints of the small flange plates have been closed down as they ought to be. The prevention of the contraction of the flange plate resulting from resistance to friction can be eliminated by measures which promote the process of contraction, for instance, by adding coupling nuts, or some similar device.

Internal tension of a weld seam, which according to the explanation set forth in Section 5 is induced in the weld seam only as a result of the welding process, must therefore be prevented mainly by skilful execution of the weld. In this connection the sequence followed when welding, the speed of welding and the number of layers run into the joint, are of importance.

The transverse tension along the joint is a result of having to run the weld metal into the groove and to cool in two separate operations. This transverse tension is proportionately less according as the field of temperature between the end of the finished part of the weld and the beginning of the weld is more uniform. This means that high welding speed is useful because it reduces the transverse tension over the length of the welded seam. In practice this transverse tension can be very much reduced by application of heat while welding (Section 7 a), or, and this is the more common practice nowadays, by welding in stages. The best method here is that called step back welding in which welding proceeds, after starting at one of the weld-ends or from the centre, by advancing symmetrically in both directions (Fig. 14). This method is particularly

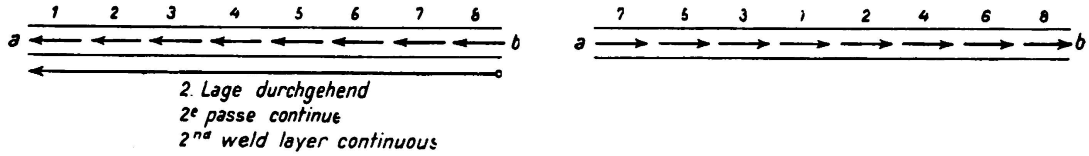


Fig. 14.

Step-back welding method.

advantageous to the first run of weld metal, because in the first place the risks of cracking (Section 6) and the overlapping of the unfinished ends of the welded joint (the latter occurs frequently in continuous welding on account of the heat that precedes execution of the weld) are considerably reduced, while the subsequent layers are often welded continuously by alternating the main directions. The stages or steps vary in length from 10 to 40 cm according to the length of the weld and the thickness of the plate; when the welded joints are very long the "steps" are sometimes still longer than the figure mentioned; tacking should be correctly carried out and at intervals equal to the length of the "steps". The so-called "welding in steps" should not be used as it tends to set up intense transverse stresses (Fig. 11, Plate 18).

The application of continuous non-interrupted welding has found great favour in ship building, which necessitates the welding of very long seams. When welding plates on to other metal members its application is practically indispensable. This method is also very useful in girder construction for the production of fairly long web connections, in particular for the welding of the first run of weld metal in the joint and probably also for long continuous weld seams.

When dealing with short lengths up to 400 mm, continuous non-interrupted welding offers no advantage. When welding medium-length butt welds of 500 to 800 mm or more, such as are commonly used in steel structural engineering, this method may be useful for root-welding if any external tension is present. As a rule, however, these welds can be executed in one operation or in two sections, and this offers no difficulty. If the joint is made in two sections and there is no external tension present when welding from without towards the centre or from the centre outwards, it is probable that a high compressive tension will be induced at the ends of the weld. With external tension a weld made from the two ends towards the centre offers more certainty that the compressive stresses at the ends of the weld and the tensile stresses will be but very slight.

The tension above the top of the weld can be reduced by applying correct welding methods, by giving the joint the right shape and by making the right number of layers. It is obvious that one sided welds, built up by a large number of thin layers, are bound to result in very unequal distribution over the section of the weld and marked peak tension in the top layers.

Symmetrical or quasi-symmetrical weld sections — alternately welded as far as possible — are generally preferable[7]. No uniform practice exists in the various spheres of application of welding technique with regard to the number of layers, the arrangement of the welding bead in the cross section of the seams, or the diameter of the welding rod. Tank designers basing their practice in the matter of welding heavy plates[8] on experience covering many years, are adopting the use of heavier welding rods increasingly. Meanwhile the layer must be neither too thick — e. g. 3 to 4 mm — nor too thin. Welding proceeds in wide layers or runs passing from one side of the joint to the other. In steel structural engineering, on the other hand, heavier welding rods are not very commonly used, in fact, exceedingly thin welding rods as compared to the heavy plates being welded are often employed. Broad layers of weld metal are not produced, generally merely narrow welds (Fig. 15) and this is made in such a way that

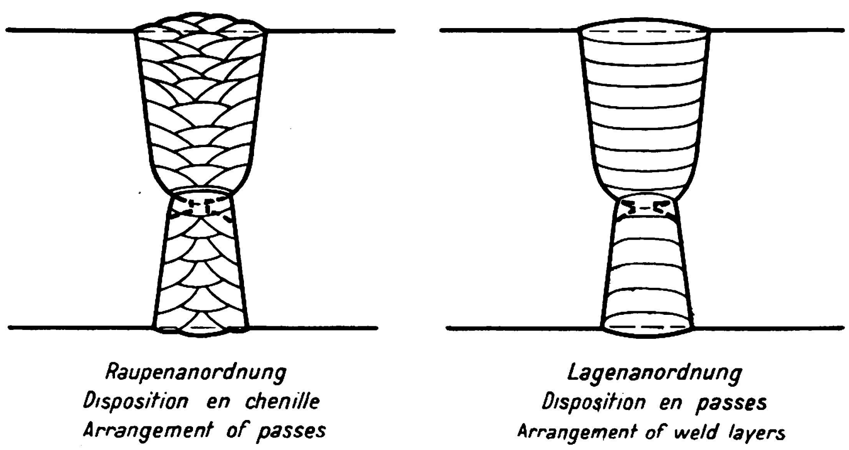


Fig. 15.

Welding of thick butt-welds.

the centre welds are executed after the side ones in order to reduce shrinkage stresses. Defects arise more easily with narrow weld than with layer welding and it would seem wise to adopt the lines followed by tank builders. Special measures might be introduced to reduce the tension further (Section 7 b).

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[7] *E. Höhn:* a. a. O. Footnote.

[8] *Joellenbeck:* Electric Welding *8* (1936).

d) Shrinkage Stresses in fillet weld joints.

When making fillet welds, only the surface of the parts to be connected are fused and no great penetration is necessary. Expansion and contraction of the weld material take place to the accompaniment of opposing tendencies in the longitudinal and transverse directions caused by the material at the sides and under the weld bead. When making a weld on the surface of a metal plate, tension conditions as shown in Fig. 16 will occur in the longitudinal and in

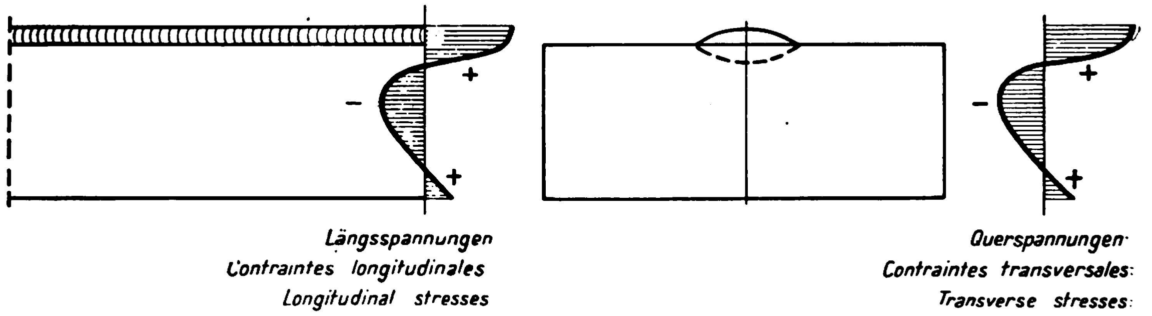

Fig. 16.

Longitudinal and transverse stresses produced by a weld.

the transverse directions, and here the maximum tensile stresses in both directions will correspond at least to the ductile limit of the material. In addition to this bi-axial stress with high longitudinal and transverse tension, there is an intense vertical tension resulting from the shrinkage stress of the two parts which are assembled. In any case the zones in the neighbourhood of all the adjacent surfaces of penetration and probably the greater part of the seam are subjected to a high degree of spacial tension coming from all sides (Fig. 17).

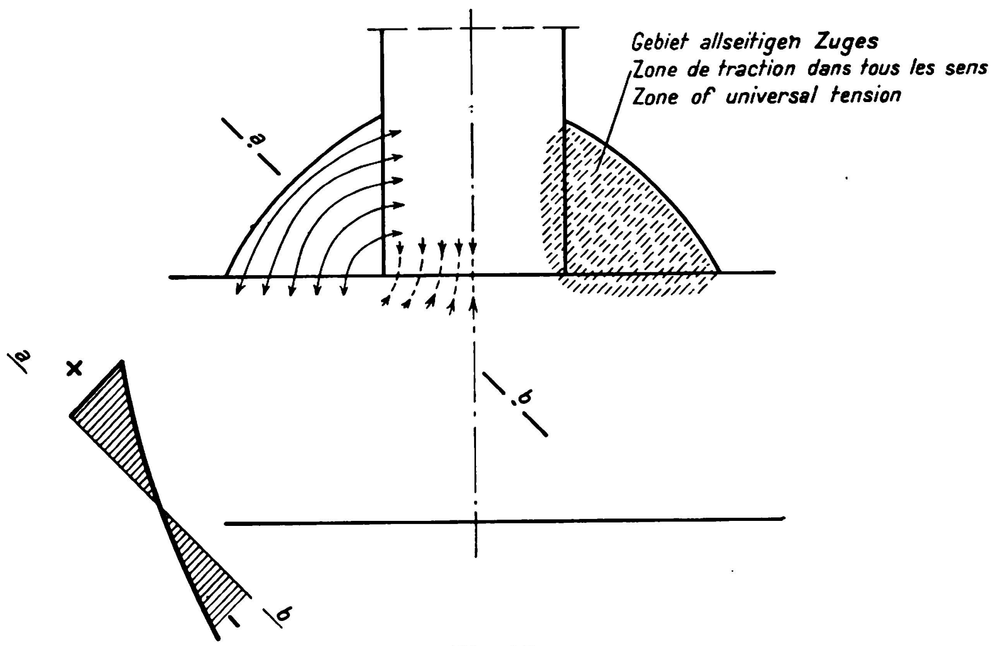

Fig. 17.

Shrinkage effects of fillet welds.

The shrinkage stress set up in $\perp$-shaped connections can be reduced by carrying out the two parallel welds one after the other and for this reason, when making long welded joints, the two welds are often zig-zag welded. When using fillets for welding plates on to structural members arrangements should be made to increase the spaces between the welds.

Fillet weld joints are more liable to crack than butt welds. This is because of the conditions of actual tension which are far less favourable. These somewhat brief statements will be supplemented in the following Section, which deals in a general way with this same problem.

6) Risks of cracking.

Cracks may occur directly after welding while the metal is still hot and during cooling at the temperatures of decreased deformation capacity, that is, at about 200 to 300° C. (zone of blue or temper heat of fracture). It appears doubtful whether cracks can result from weld stresses even after cooling unless there is some additional stress exercised from without. Probably in most cases the cracks which have occurred were caused by high temperatures; even cracks that appeared only after welding were perhaps started while welding was proceeding. (No account is taken here of cracks in tacked parts nor of those in the welded joints which occur when other parts of the joint are being welded.) In many cases cracks were recognized as being definitely due to heat effects ($t \geqq 600^{0}$ C).

It is therefore necessary to base estimates concerning risks of cracking and decisions providing precautionary measures mainly on the behaviour and the properties of the weld material at high temperatures. Consideration of the state of tension observed when the metal has cooled down can easily lead to erroneous conclusions. Weld metal used in this connection should be interpreted as being the mixture of melted welding rod and the melted parent metal.

The thermal coefficient of expansion for steel at indoor temperature is $1.1.10^{-5}$ (per degree); above 100° this figure increases gradually. The entire shrinkage of the weld metal (melted rod and melted parent metal) when contraction proceeds freely and when cooling has brought the metal from 700° C to indoor temperature is about 1 per cent. When clamping exists there is an additional shrinkage due to the obstruction of the neighbouring zones which have been heated to a higher temperature; the extent of this shrinkage depends on the various structural conditions (degree of tension) and on the welding conditions *Wörtmann* and *Mohr*[9] have published further detailed information on this matter, laying down a figure of 4—6.5 per cent. for the entire contraction in a specific case where circumstances were very unfavourable. As for the coefficient of elongation of the melted welding rod, with the rods commonly used nowadays, this figure could be considerably exceeded, particularly for high temperatures, and it would then be hard to explain the presence of cracks.

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[9] *F. Wörtmann & W. Mohr*, Calorific Stresses in Welds and Influence on Safety Factor in Finished Structures. Swiss Building Review, Vol. 100, Pp. 243/246.

For the production of diagonal joints on plates 12 mm thick (unalloyed steels and steels up to those with high carbon content) ($\leqq$ 0.7 per cent.). *Zeyen*[10] laid down that risks of cracking while in the hot state existed when using C $>$ 0.4 per cent., together with heavily coated electrodes E 52 h (specification of the German State Railways). On the other hand when using lightly coated electrodes and alloy-core electrodes which mostly have a lower angle of flexure and less resiliency, risks of cracking at high temperatures disappeared. These phenomena can doubtless be explained by the fact that the amalgamation of the two last-mentioned rods with the basic metal was less intimate and therefore better in this case than the heavily coated electrodes. Thus the rods which generally were unsatisfactory from the point of view of deformation were found more suitable in special circumstances.

When weld stress occurs, the tensile state is always of a duo-axial and most often, particularly with fillet welds, of a tri-axial kind, and this is why resistance to thermal ductile limit and the coefficient of elongation, which are determinate quantities in the uni-axial state of tension, cannot serve as a criterion for gauging crack-proof qualities. As it is scarcely possible to obtain enlightenment concerning the standard internal state of cohesion of the mixture of electrode and parent metal at high temperatures and under the stress in question, there is no choice but to resort to empirical methods and experiment on tendencies to crack. See Fig. 1. When this type of experiment is made, a general picture is obtained of the properties of the material and the moulding capacity of the melted weld metal. It is my opinion that in this connection the problem of shape plays no small part in influencing the course taken by the forces of shrinkage.

With reference to the fillet welds shown in Fig. 17, if the triangular seam is limited by straight lines, the main lines of tension may be expected to follow an unrestricted course owing to shrinkage forces. Where joints are definitely concave, there will be an interruption of the course of the flow of forces near the surface with corresponding peaks of stresses (Fig. 18). This is why concave welds break more easily than seams of more or less triangular section. Incipient cracks which appear so frequently at the ends of hollow craters might very easily be largely due to this fact. The marked preference for hollow or grooved seams, resulting from a knowledge of their dynamic behaviour, should be restricted as far as possible because of shrinkage effects, and this is all the more desirable because, in the case of alternating stresses, the concave weld surface is a less important factor than the gradual transition from surface of the metal plate to surface of the weld, and with regard to certain stresses (shear welds) the importance of this aspect should not be unduly exaggerated[11].

When dealing with this kind of tension in connection with butt welds the shape of the various runs or layers of weld metal is of importance, because if the weld bead has a wrong shape cracks will be induced more easily than where the reverse is the case, even if all other conditions are equal (Fig. 19).

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[10] *K. L. Zeyen:* Welding of Unalloyed Steels of Great Strength. Steel & Iron *56* (1936), Pp. 654/657.

[11] *G. Bierett:* Design and Execution of Welded Structures Based on Research Work Concerning Tension and Resistance. Electric Welding *6* (1935), Pp. 141/150.

If the welds are too thin compared to the thickness of the basic metal, and this is particularly so in the case of the first layers run into the joint, cracks will occur very easily. When butt welds are being made a first layer which is too thin compared to the

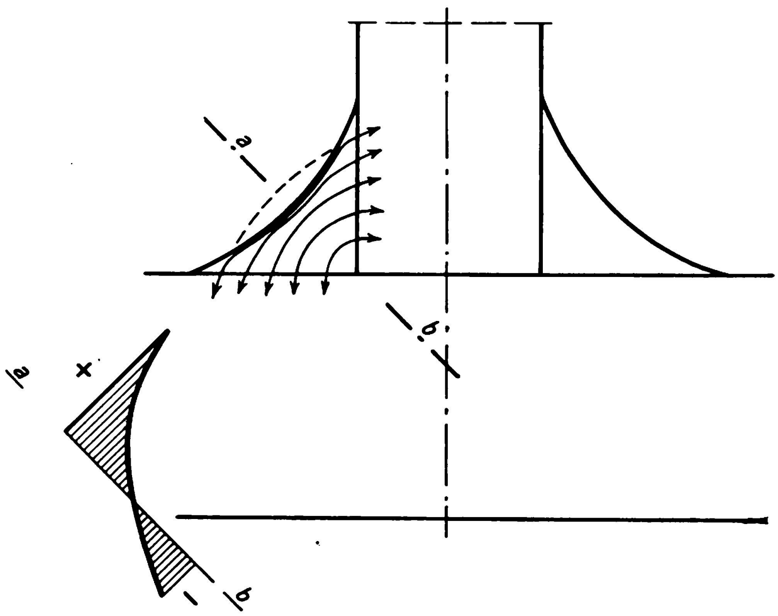

Fig. 18.

Shrinkage effects of distinctly concave fillet welds.

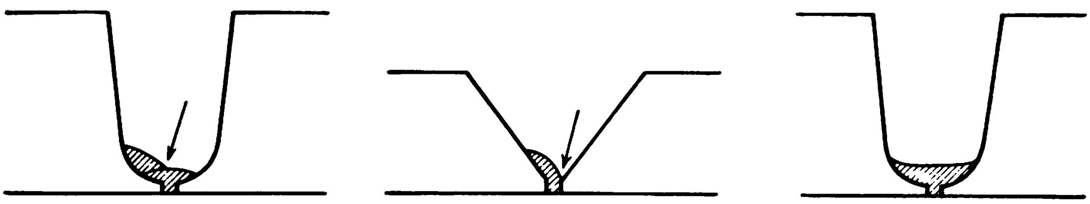

Fig. 19.

Danger of cracking when shape of weld unsuitable.

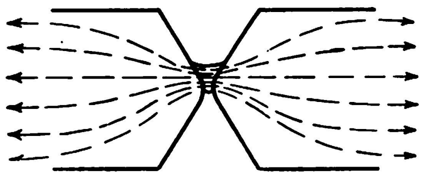

Fig. 20.

Endangering of weld-roots due to unfavourable flow of forces.

somewhat heavy plates will generally break under the tension present, because the flow of forces alone is a very unfavourable one (Fig. 20). Most cracks start at the root of the weld and that accounts for the common practice in tank construction of strengthening the first layer run into the joint and the thin portion of parent metal below by diagonal reinforcing straps placed at the rear of the weld (Fig. 15). In order to avoid the occurrence of cracks in thick seams, welding should proceed without any interruption until the groove has been filled up to a certain height. When welding first on one side and then at the back by turning the whole job round, a certain height should be reached in the groove before going on to the other side. When welding plates[12] around the whole circumference and using St. 52 as basic metal, it was found that the formation of cracks could be prevented by welding over the whole width of the seam (made in several layers) for each individual section welded, before passing on to the next section.

With fillet welds in which the first layer was too thin as compared to the thickness of the work in hand, cracks occurred in nearly all cases. When carrying out thin welds the part to be welded on to the structure was not sufficiently heated and its plastic properties did not extend deep enough, with the result that the stress effects were very great (Fig. 21).

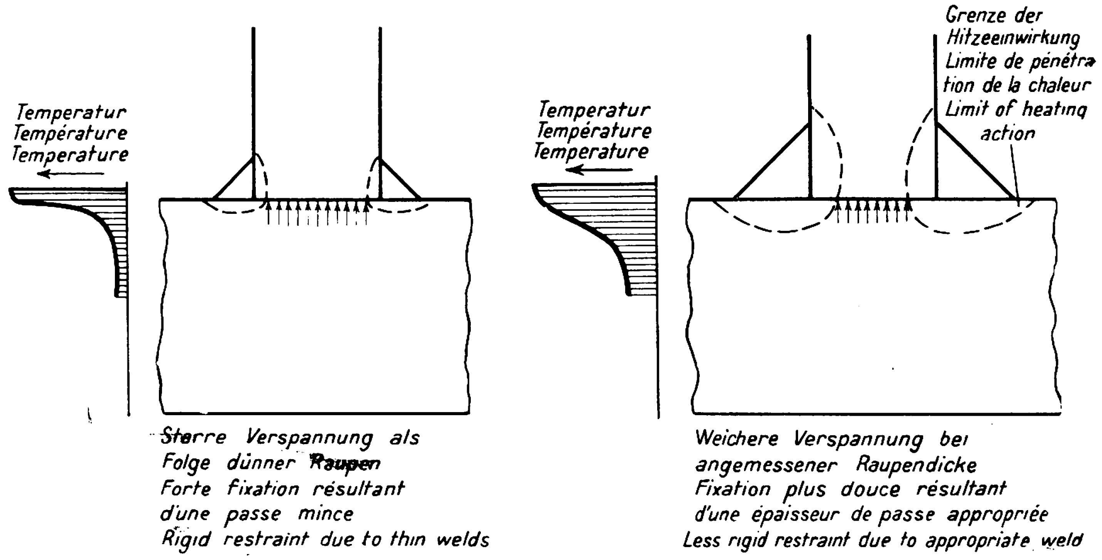

Fig. 21.

Restraint action of fillet welds.

When welding unduly thin beads to heavy pieces of metal the quenching effects were so great that with highly resistant steels, it was found that the zones of penetration exposed to tri-axial stresses had cracked. When this occurs the weld will be found to peel off the basic metal.

The thickness of the weld must be in proportion to the thickness of the material and in no case too small. (This is a point which should also be noted when leak-proof joints are being made on heavy members.) The instructions concerning conditions previous to welding when using thin rods must not be interpreted too narrowly.

In girder construction difficulties of the kind described may be largely avoided in connection with the collar welds by using spe-

[12] *H. Bühler & W. Lohmann:* Contribution to the Problem of Weld Stresses. 3. Cont. Actual Stresses in Welded Patches. Electric Welding *5* (1936), Pp. 221/229.

cial sections, such as "nose sections" (Union), bulb iron sections (Doernen) and S.T.-sections (Krupp). The main advantage of all these sections lies in the fact that the less massive parts which are rolled, namely: nose, bulb or web, increase heat maintenance and prevent unduly rapid cooling. In order to prevent cracking, these or similar sections should be used and this should be done increasingly where the metal is thicker or stronger.

7) Special Measures to reduce Stresses and Risks of Cracking.

a) Thermal Measures.

Special thermal measures can be applied during and after the operation of welding. They aim at preventing cooling proceeding in a similar way to quenching, reducing the danger of cracking while welding is being carried out, inducing more equable stress conditions along the length and across the width of the seam and reducing the longitudinal stresses in the zones of the weld. According to circumstances, one or other of these points will be more important and thus the thermal measures which are applied must be in keeping with these circumstances.

1. Preheating should be carried out when massive parts are being welded, and particulary in the case of hard steels, before the first layer is run into the joint. Steel structural engineering should make greater use than it does at present of pre-heating for weld seam edges or penetration surfaces. Where the weld is unilateral, for instance, when making a ⊥-section, more intense preheating may result in the metal at the final stage presenting no defective curves.

2. Heating of the sections of the weld which have been finished while welding of the later sections is still proceeding may reduce the stresses in long joints and in thick ones, with the consequence of reduction of crack occurence[13]. When making long seams which are welded without interruption, it is advisable to aim at obtaining a more even field of temperature by heating the welded joint after completion; in particular this should be done to the first layers run into the joint as these are particulary exposed to crack formation.

When making thick seams which are exposed to external or internal stresses, particularly those susceptible to cracking on account of the thinness of the first layers (Fig. 20), contraction may be prevented by keeping up the temperature of those layers by subsequent heating, and this should be continued until the seam has been built up sufficiently to resist stress. In the case of very thick seams the welding operator should heat the rear side subsequent to welding, and this should suffice to reduce stresses in that part of the weld. Meanwhile, it is quite likely that these very beneficial measures have been rarely applied so far.

Where these intense stresses are present the zones neighbouring on the welds can be heated while welding is proceeding.

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[13] *G. Bierett:* Application of Knowledge Concerning Stresses to Working Methods when Making Butt Welds for Steel Structures. *9* (1936), Pp. 69/71.

The thermal measures mentioned above serve to prevent cracking while welding is being carried out. However, it is not very likely that the remaining average transverse stresses will be less than where additional heat is not applied; it is more probable that the reverse will be the case. To counter-balance this, however, mechanical measures — in particular, hammering — can be resorted to (Section 7b).

3) Heating subsequent to welding can be applied in order to equalize any very marked uneven stress conditions within the weld seam, either along it or across it, in order to reduce the longitudinal stresses very considerably. When external stresses or some similar condition exists (welding tests, patching, for instance), there is no certainty that the average transverse stresses will be reduced. A very useful means of combatting unequal tensions can be obtained by heating the metal to a deep red glow[14]. Subsequent heating of lines along the welding zones at temperatures of from 550 to 600° C. may reduce the longitudinal stresses in the welds very considerably[15]. This method has been applied when welding very heavy tubes[16]. This intense heating may, however, induce greater warping, and the methods should therefore be used with great care.

Generally speaking, intelligent application of heat will result in improved quality of the weld. Methodical application must, however, be based on expert knowledge.

Welders should be warned against employing measures to accelerate cooling or to maintain the parts to be welded cool by artificial means. Such means may, as a matter of fact, prevent bending or warping, but they generally increase the stresses. Heat should be allowed to escape from the welded joint and to pass through the parts to be joined without any artificial means. (Special cases in which artificial cooling is useful and has no deleterious effects hardly arise in steel structural engineering.)

b) Hammering.

The welds, or the zones in the neighbourhood of the weld are hammered. This is done either when the metal is red hot or when it is cold.

Hammering when the weld is red hot necessitates having malleable weld metal. In the past this method was mostly applied for gas fusion welding only, but it is now used for electrically welded butt welds. Its aim is not to reduce stress but to make the joint more leak proof; it is also used in connection with correcting defects such as sag or bend. Hammering the zones near the seam while ie a red hot state relieves an unfractured weld under great stress; as far as I know, it is not much applied in steel structural engineering.

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[14] *G. Bierett & G. Grüning:* Shrinkage Stresses in Oxy-acetylene Welded Parts. Autog. Metalworking. *27* (1934), Pp. 259/266.

[15] *Ebel & Reinhardt,* Measurement of Stresses in Welded Circular Seams. Autog. Metalworking. *27* (1934). Pp. 305/310.

[16] *R. Schmidt:* Observations on the Problem of Heat Treatment Subsequent to Welding when Engaged on Large-scale Jobs. Electric Welding *6* (1935), Pp. 231/232.

Cold hammering of the joint requires above all suitable weld material which will not be liable to microscopic cracks or to brittleness. Hammering of welds reduces longitudinal and transverse stresses and when the zones neighbouring on the weld are hammered the idea is to reduce transversal tension. With thick weld seams intermediate layers are inserted so as to prevent excess tension and bending; these are hammered into position in the centre of the weld.

Hammering also calls for expert knowledge concerning the materials being used.

Summary.

Welding is a complicated metallurgical process. The occurences which take place when the welding zones are cooling lead to the formation of cracks when material of a certain composition or of unfavourable cooling speed is being used. The parent metal and the welding rods required in steel structural engineering must consequently be selected for their crack-proof qualities. Welding rods which produce weld metal tending to crack should be eliminated right from the start by appropriate tests carried out previously, and the same applies for rods which melt too rapidly when undue heat is applied.

Weld material, if its movements are unrestricted, contracts uniformly in all directions. Practically, this possibility of unhampered movement is present only in the transverse direction and then only in butt welds which have been executed with great rapidity. The extent of the transverse contraction depends on the size of the section of the weld and the specific heat consumption of the welding rod, and this should therefore be as limited as possible. Alongside the transverse contraction angular contraction takes place in the thicker welds; its extent depends mainly on the shape of the section, the size of the weld and on the number of weld layers made. Transverse contraction is lower in fillet welds than in butt welds. Longitudinal contraction is always less intense than transverse contraction as not only the expansions of the heated zones, but also the shrinkages in this direction are hampered by the colder zones. This obstruction causes intense longitudinal contraction, the size and course of which, on both sides of the joint, depend on the width of the zone of heating. Reasons connected with equilibrium cause longitudinal stresses to be always followed by transverse stresses; this means that it is not possible to weld without inducing transverse stresses. Intense compressive stresses are set up at the ends of the weld joints, transversally to the welded seam, and in the centre tensile stresses arise. This state of transverse stress is also found in the neighbourhood of welds of medium length and great depth.

The longitudinal shrinkage stresses are of particular significance for the welds which run uninterruptedly in the main direction of forces. As the longitudinal weld stresses are very intense, it is advisable where welds are under tensile stress to avoid unduly narrow heating zones, as these set up particularly intense stresses in the weld. On the other hand, with structural members exposed

to risks of bending, great care should be taken to keep down the compressive stresses of reaction which maintain equilibrium of the longitudinal weld stresses; this can be effected by restricting the weld sections and by executing the weld with as limited an amount of heat as possible.

When making a weld, transverse stresses of more or less intensity are practically always set up. A distinction must be made in this connection between external and internal stresses. The external stresses depend on structural conditions. The parts to be welded together are fixed before beginning to weld. The internal stresses of a weld are due to the fact that melting, running the weld metal into the joint, heating and cooling of the various parts of the joint cannot be done in one operation but have to be carried out successively. Intense stresses are set up in fillet weld connections and when welding plates into or onto larger members.

One of the main conditions underlying the reduction of external and internal stresses is that of keeping down the dimensions of the weld sections, and the elimination of welding rods which require an unnecessarily large specific heat supply. Stresses of the external kind are reduced most effectively by elastic shaping of the parts adjoining the joint, and by appropriate sequence of the various welds. Prevention of shrinkage, for instance, by friction resistance of massive parts, can be eliminated by measures which encourage the proces of contraction. Internal stresses in a weld seam above the length and height of the seam must be combatted above all by increased welding speed, sequence of welding operations and avoidance of too many layers.... Continuous non-interrupted welding is advantageous when making long welds and above all when running the first layers of weld metal into the joints as this latter is especially prone to cracking. The stresses at the top of the weld can be reduced by giving the joint a symmetrical form and by alternately welding front and back of the joint and by limiting the number of layers.

Conditions governing weld stresses are far less favourable for fillet welds than for butt welds, as the zones of welding are exposed to intense tensile stresses on all sides. The two joints of ⊥-shaped connections should be welded one after the other, the length of expansion between the two parallel fillet welds should not be too short if contraction is to be reduced. As a general rule fillet welds are more liable to crack.

As a rule the cracks occur while the material is hot and during cooling in the zone of temperature in which the coefficient of deformation is lower. (Zone of tempering fracture.) Gauging the risks of cracking and providing measures to prevent this must therefore be based mainly on the behaviour and properties of the weld material at high temperatures. The coefficient of elongation for the uni-axial state is of no use as a criterion for gauging the risks of cracking. Appropriate tests must therefore be carried out in order to determine the crack-proof qualities of the material. The shape of the section of the seam plays some part in ensuring safety against cracking. Definitely concave welds break easily compared with seams of approximately triangular section, as in the case of the concave welds unfavourable conditions of actual stress arise. Welds with marked notches tend to crack easily. Welds that are too narrow in proportion to the thickness of the material, and in particular, layers at the root of the weld which are too thin lead easily to cracks. For this reason the thickness of the weld must be in keeping with the thickness of the material being used. When making thick butt weld joints the welding must proceed without interruption until the joint is fairly well filled. In girder construction the carrying out of the collar welds can be facilitated by using specially rolled sections.

Special heat treatment, prior to, during and after welding, aims at preventing cooling of a quenching nature, and also at reducing risks of cracking while welding is proceeding. It is also applied in order to obtain more equable tensile conditions along and across the weld and to reduce longitudinal stresses in the welding zones.

Cold hammering of the weld can only be done with weld metal that does not tend to form microscopic cracks and does not incline to brittleness when hammered. Hammering is a useful means of reducing stresses left in welds after the welding has been terminated.

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IIIb 4

Design and Execution of Welded Structures.

Ausbildung und Herstellung geschweißter Bauten.

Projet et exécution des ouvrages soudés.

Dr. Ing. St. Bryła,
Professor an der Technischen Hochschule Warschau.

Secondary and shrinkage stresses occur in every welded joint in the weld and the parent metal. The internal stresses of the weld are set up by the difference of temperature between the weld and the neighbouring metal. They are independent of the method of clamping of the members to be welded and always appear in the weld, even when the parts to be welded are not clamped together. Their origin lies in the heating and the shrinkage of the heated area. The cool or only slightly heated metal surrounding the weld entirely prevents any shrinkage in the latter during cooling.

In the metal of the parts to be assembled, stresses are set up through the edges of the parts being gripped by means of hand clamps, in order to prevent any shifting while being heated. The greater the area heated, the smaller the stresses in the weld and the greater those occurring in the structure. When flame welding is employed, the greater stresses occur in the structure, those in the weld being greater when electric-arc welding is adopted, in which case they may often reach the yield point. However, the yield point may rise to an appreciable degree, in consequence of the resistance to deformation set up by the irregular rates of shrinkage.

The thickness of the parts to be welded has a great influence on the amount of the internal stresses. Stress reactions do not increase in direct proportion with the thickness of the parts, though, nevertheless, they do become considerably greater. Shrinkage stresses also increase with the length of the weld. The longer the weld, the less uniform is the distribution of stress and, consequently, the resistance of the weld. The tests carried out by the author and Dr. Ing. *Poniz* at Lwow (Lemberg) have shown that the stresses at the end of the weld are much greater than (often twice as great as) the stress midway along the weld[1]. For a given length of weld, a limit is reached beyond which the resistance of the weld remains practically constant. Shrinkage stresses operate only in definite directions and it is not until the girder begins to be strained that the total stress is reached in the joint. The important and, even in certain cases, predominant influence of the shrinkage stresses shows that similar effects develop in the case of interrupted welds, where the welds at the end are subjected to much

[1] The stresses in the welded members are similarly distributed.

greater stress reactions than those at the centre. Nevertheless, the stress distribution is much more uniform in the case of interrupted welds.

However, these strong internal stresses in the weld are not dangerous; chiefly because, as a rule, the external forces act only in one direction and the internal stresses due to shrinkage act in three directions, and also in consequence of the plastic properties of steel. As proof, reference may be made to the results of all the tests carried to rupture point, and also to the quality of well executed welds.

Even when cracking occurs in the weld — which happens very rarely — the cause is not to be found in the stresses due to shrinkage, but in the brittleness of welds carried out with unsuitable material or in an indifferent manner.

As is shown by our tests, a weld behaves better when its properties approximate most nearly to those of the parent metal, and, primarily, has an identical yield point. The use of electrodes composed of material having a resistance far exceeding that of the metal to be welded cannot therefore be always recommended. The production of welds having the same elastic properties is far more important. The use of sheathed electrodes, which give much better results than bare electrodes, can therefore be recommended.

There are several methods for the treatment of welds with a view to the reduction of internal stresses. All our attempts in this direction are, however, negative, because the trouble entailed is uneconomical. The lowering effect on the shrinkage stresses is relatively slight, and in consequence, is devoid of import when these methods are employed. In view of the innocuous behaviour often displayed by these stresses, there is nothing to justify subsequent attempts for their reduction. These methods have a rather different significance; cold working, for example, producing a finely grained structure and therefore augmenting the resistant capacity of the material. A weld on two sides also acts, in a certain degree, like cold working and enables faults in welding to be rectified. The same applies to the different passes in the case of electric-arc welding, the earlier passes being consolidated by their successors.

The stresses of construction (erection) are the internal stresses set up in the parent metal, during welding, in consequence of the parts to be welded being gripped by means of clamps.

Although by using these latter the deformations of the structure are reduced to a minimum, or even eliminated entirely, the said clamps set up internal stresses in the parts to be welded, which are proportional to the deformations and shifting that is to be prevented. The extent of such shifting depends upon the size of the pieces to be heated and welded. That is why the stresses of construction increase in a manner corresponding to these factors.

The stresses of construction are devoid of spatial characteristics and form planar and even linear systems. They do not raise the yield point of the material and their values are very much lower than the shrinkage stresses in the weld.

Although, given suitable metal and satisfactory welding, the shrinkage stresses are not in themselves dangerous, yet it is essential to eliminate, as far as possible, secondary stresses in all metallic structures. This same necessity also exists in the case of welded structures and their shrinkage stresses. It is advisable to perform the welding of the parts in such a way that so far as is possible, they are free from any pre-existing stresses. The suitability of various influences which in a certain measure are mutually destructive, should be considered. This counteraction occurs, for example, in thick welds (see above) in which, however, the determination of the various magnitudes of such influences

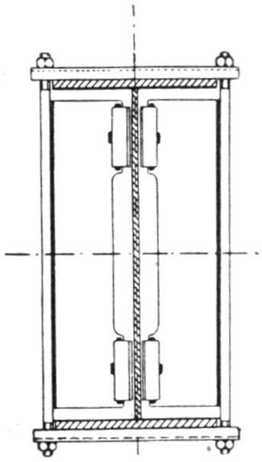

Fig. 1.

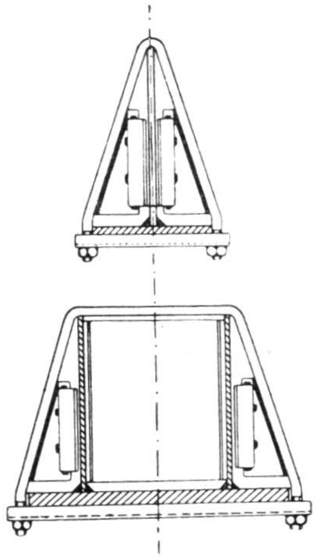

Fig. 2 and 3.

is not altogether easy. Thin welds should also be longer, which can be considered as a negative factor from the point of view of shrinkage stressing. The variety of opinions regarding the employment of thick or thin welds should not, therefore, occasion surprise. On the basis of numerous tests, the author is rather

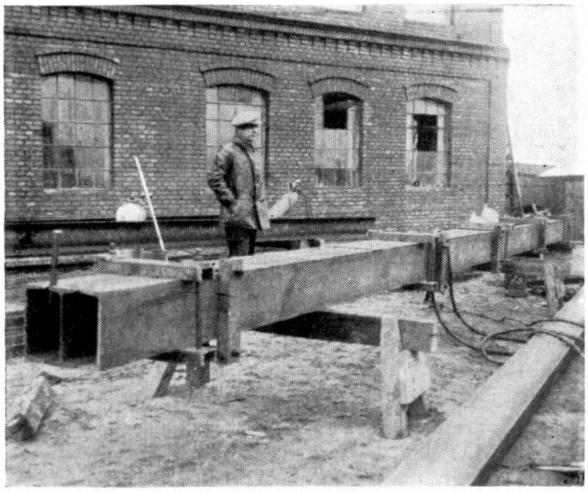

Fig. 4.

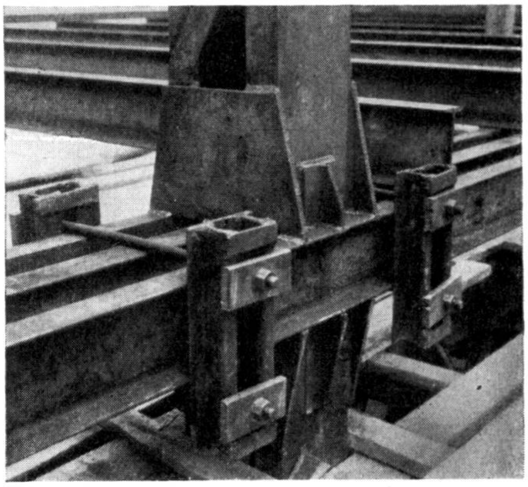

Fig. 5.

inclined to consider thin welds better and stronger, besides being cheaper. The negative influence of their unavoidably greater length can be overcome by making them in short sections, subsequently filling up the gaps which probably remain.

A second hint, which is applicable in all cases, is that the electrodes used should, so far as is possible, consist of a metal similar to the parent metal, particularly in respect of elasticity. The increased resistance, though very important, is less significant. The use of sheathed electrodes can be recommended.

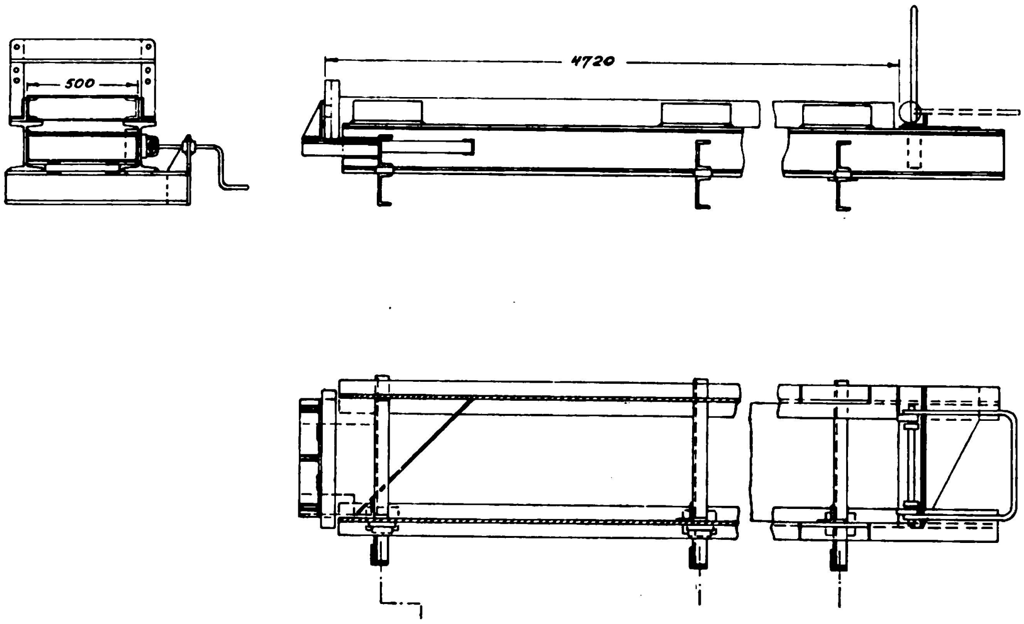

Fig. 6.
Bracing arrangements for the fabrication of columns for the Jagellon Library in Cracow.

Thirdly, the shape of the weld should be, if possible, smooth and devoid of angles.

Other influences reducing shrinkage stresses must be considered of secondary importance.

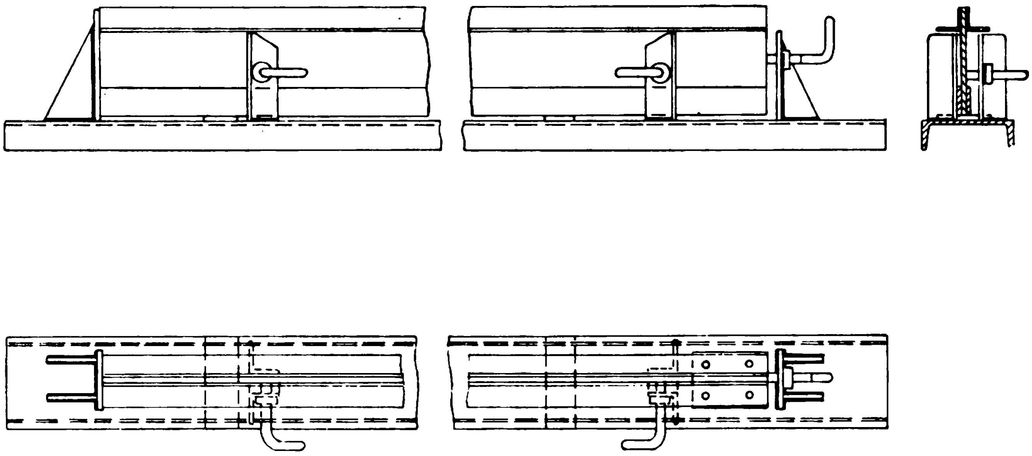

Fig. 7.
Clamping arrangement for the fabrikation of beams and girders for the Jagellon Library in Cracow.

The deformations produced by the stresses of construction are more important in their effects than the said stresses themselves. The author is not of opinion that all the deformations should be avoided at all costs. Clamps are, however, always necessary because the character of the parts to be welded — composed, as they are, of several pieces — demands them. Plate girders, the members of framed girders and their welded parts, are not provided with angle sections which, like those in riveted structures, are adapted to serve as junctions and, at the same time, fix the relative position of the plates. This is often one of the factors which enable a saving of material to be made in the case of welded structures; but, on the other hand, this fact makes the assembling of the pieces more difficult and entails the use of hand clamps. It also results in a tendency to deformations due to erection stresses, so that, for placing the sections in position, some clamps are still necessary in order to lessen these deformations.

This circumstance is decisive as regards the shape and construction of the clamps jaws, which should be precisely adapted to the shape of the parts to be assembled in such a way that the latter can be inserted. For this reason the clamps are generally provided with self-locking pieces — as a rule, a threaded iron bolt and nut. An example of such clamps is the type used as early as 1926 for assembling the cross girders and members in building the bridge over the Studwia at Lowics (Fig. 1) and which proved so successful that clamps of the same type were used in 1934 in the construction of the bridge on the Wiesbaden-Frankfort road (1935 N). A second example is afforded by the type used in the case of the Post Office Savings Bank at Warsaw (Fig. 2). Still another example is given in Fig. 3. In conclusion, Figs. 4 and 5 illustrate more complete, but also more complicated, clamps which were used in building the Jagellon Library at Cracow, where perfectly smooth shapes were particularly needed, and where the complete elimination of all deformations was essential.

Summary.

The Author starts his paper with a description about secondary and shrinkage stresses, and continues by explaining the means which have to be adopted for reducing these stresses. He describes a number of various types of clamps which are used in Poland for the purpose of reducing such stresses in welded constructions.

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IIIb 5

Shrinkage of Welded Trussed Structures.

Schrumpfungen in geschweißten Fachwerken.

Retraits dans les poutres réticulées soudées.

Dr. sc. techn. S. Mortada,
Brücken-Ingenieur der Ägyptischen Staatsbahnen, Kairo.

The shrinkage causes changes in the workpiece due to the resistance of the metal parts against the tendency of the hot zones to retract when getting cold. This phenomenon causes changes of length as well as waving and rotation in the different elements of the structure.

The shrinkage and the internal stresses caused require special care in the case of welded trusses, as the capacity of bearing of such structures, especially for repeated loads, is dangerously reduced by the internal stresses.

A short time ago we made a large number of shrinkage measurements on a test steel truss. The truss was afterwards statically and dynamically tested in detail in the Federal Institute for the Testing of Materials, Zürich.

The aim of these measurements was to get definite knowledge of the different kinds of shrinkage and their values, as they happen in actual welded structures.

The test girder measured 6 m in length and 1,5 m in height and was dimensioned for a load of 50 tons applied in the middle of the span.

The bottom chord was composed of two angles 80×12 mm, the top chord of two angles 100×12 mm and a plate 100×12 mm. All the diagonals were built of two T-sections No. 14.

The joints of one half of the girder were carried out with 12 mm butt V-weld with welded roots, those of the other side were designed with fillet side and front welds of different thicknesses and lengths.

The end joints of the one diagonal were composed of side fillet welds 8 mm thick and 27 cm long, those of the other side of 11 mm resp. 19 cm.

In the top chord there were two 12 mm V-welds, running along a length of chord of 3,60 m.

The connections of the diagonals as well as of the gussets to the top chord and in the middle of the bottom chord were made of two V-welds of 60 cm length and 12 mm thickness.

The thicknesses of the welds mentioned above were necessary to enable satisfactory transmission of the forces. They are relatively big compared with the small dimensions of the girder. Large amounts of shrinkage were therefore expected from the beginning, so every precaution to avoid their development was observed, but it was of course not possible to prevent them totally.

In spite of this, mantelled electrodes were used as from the metallurgic point of view they are to be preferred, although they increase the shinkage. High current was applied in order to increase the rate of melting. For the welding, electrodes of 4 mm diameter of the Swiss make "Arcos Stabilend", joined to

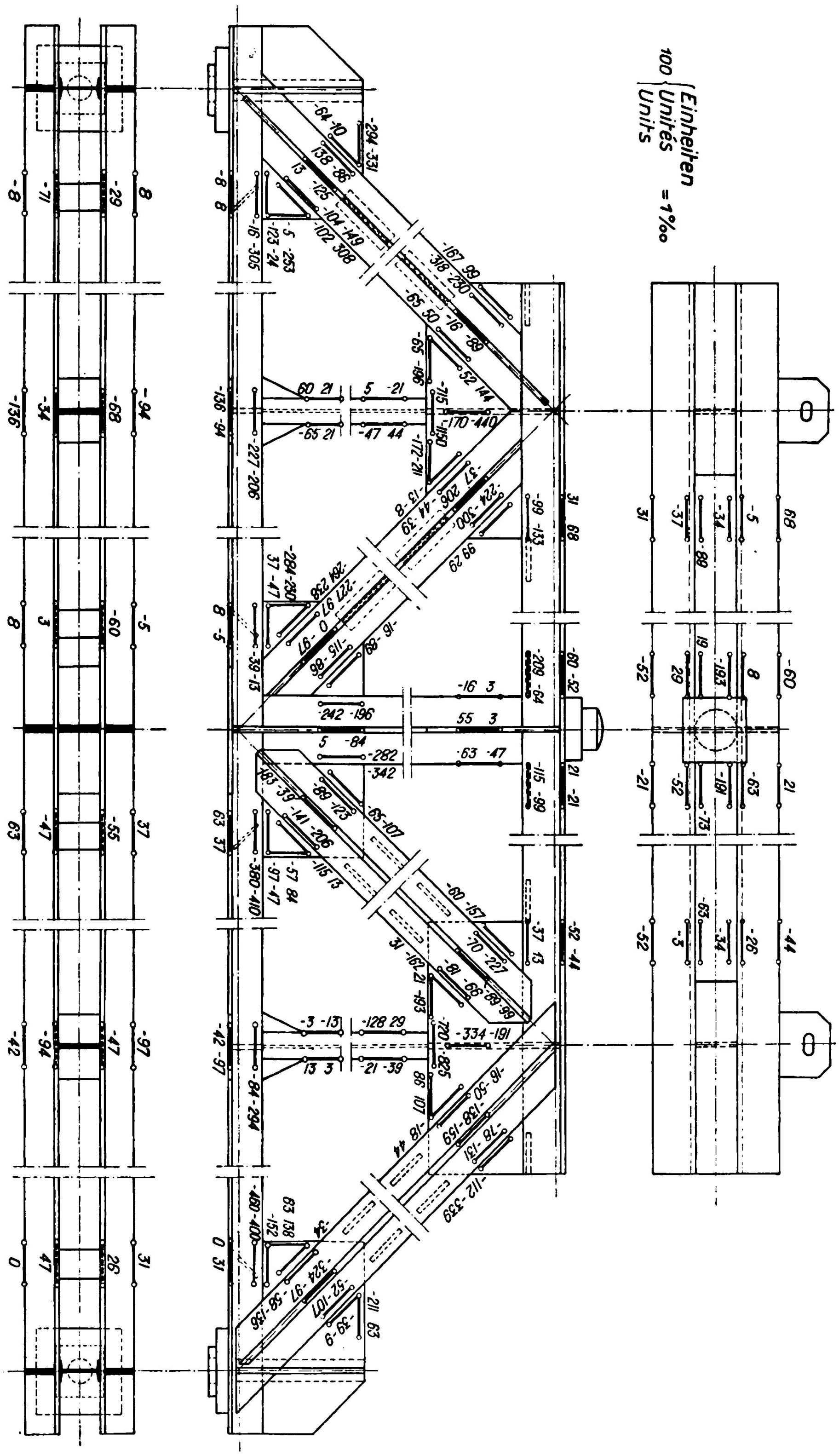

Fig. 1.
Measured shrinkages.

the positive pole, were used. The current reached 200 amps. at abt. 27 volts during the welding.

Execution of the welding.

The welding of the girder was carried out in such a way as to ensure free expansion without any external hindrance to the parts under welding; only when welding the end diagonals this was no more possible as the girder had finally to be joined together.

At first, every member of the girder composed of several pieces was welded together, beginning with the welds in the middle and allowing expansion on both sides. The welding was then continued symmetrically from the middle.

The same order was followed when welding the whole girder. In this way we tried to reduce reaction stresses due to hindrance of free expansion of the hot parts.

In spite of these precautions, remarkable shrinkage appeared. Most striking was the effect of the long welds in the top chord, which caused strong rotations in the chord angles and reduced the free distance between the inside surfaces of these angles from 100 to 96 mm.

It is to be mentioned that — to retain the distance of 100 mm between the chord angles during the welding — rolled sections of 100 mm height were used as distance pieces. The influence of the shrinkage after the cooling down of the finished welding of the top chord was so strong, that it was very difficult to remove the distance pieces. The webs of two of them were buckled and to avoid forcing it out, of a third one the web hat to be burnt.

Measuring of the shrinkage and test results.

The determination of the shrinkage is based on the accurate measuring of the distance between two points in any part of the girder before and after the welding. The difference thus found is mainly due to shrinkage; a small part of it may be due to erection, but — as the fitting together of the different pieces was done very carefully — this could not be considerable.

The changes of length were measured with a Deformator of the Huggenberger type, which allows accuracy up to 0,00261 mm. The distance between the points of the apparatus is 10 cm. This length made it difficult to do any measurements across the seams, so that principally measurements along the seams and the edges of the gussets were carried out.

In each end joint of a member, measurements were carried out along the edges and in the middle, the former were chosen as near as possible to the welds. Other measurements were made in the gusset plates along the welds. Totally there were 212 measuring lengths.

Every length was measured four times; after every measurement the instrument was turned so that its points were changed. The difference between the readings was not to exceed two divisions of the instrument scale = 0,00522 mm. Moreover, the influence of the change of temperature during the measuring was taken into account.

The results of these measurements are given in Fig. 1. The +sign denotes elongation, the —sign shortening. The two values given for each point correspond with both sides of the girder.

The numerical values show big differences, no rule can be derived.

The shrinkages close to the welds are very considerable. They cause bending in the sections so that big changes of length in the outside edges of the latter were measured.

The resulting stresses are not in proportion to the shrinkage, as the latter takes place to the greater part when the material is hot, without practically causing any stresses.

Inspite of this, the shrinkage caused high internal stresses, which lead the material in some places to yielding, but no cracks could be found.

In the fatigue-test, the girder was broken after only 1,4 millions of load repetitions ranging between O and the working load for which the girder was dimensioned, i. e. without raising the limit of loading.

The following conclusions were derived from these tests:

1) The shrinkages do not occur uniformely. No rule can be made for their magnitudes.
2) The shrinkage in the welded trusses reaches very big values, due to the small dimensions of the parts and the relatively big welds. They cause strong rotations in the sections and wavings in the gusset plates.
3) The internal stresses due to the welding can be so high, that they cause the material to yield in some places.
4) The resistance of the welded trussed girders for alternating loads is dangerously reduced by the thermal stresses. The strength of the material to repeated stress is exceeded under the action of the load for which the girder is dimensioned.

The application of the welded trusses requires therefore a lot of care in cases where high dynamic stresses are to be expected.

Summary.

The author describes some of his investigations about the amount of shrinkage. The adopted welding procedure and the mode of taking measurements are explained. The author recommends utmost caution for welded lattice construction if subjected to alternating efforts.