# Welded Connections in Cold-formed Sections

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# WELDED CONNECTIONS IN COLD-FORMED SECTIONS

by Jan W.B. Stark[1)] and Frans Soetens[2)]

SUMMARY

In this paper the results of European research on welded connections in cold-formed sections are reviewed. Recommendations are given upon the welding technology and the structural design of connections. Design strength formulas are proposed for spot - and fillet - welded connections.

## 1. INTRODUCTION

In addition to the interest in hot-rolled steel sections, the application of cold-formed steel sections is increasing. The welded connections in these sections and in sheet steel differ significantly from those in hot-rolled sections. Important differences are:

- The mechanical properties of the parent material are influenced by cold-forming and welding.
- The welding methods used. Except for fusion welding techniques which are similar to connections in hot-rolled sections, resistance welding is frequently used with connections in thin sheet.
- The weld types which can be divided into spot, fillet, seam and butt welds
- The shape of the sections, the type of connection and the small sheet thickness which influence the structural behaviour of the joint.

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Because of the little knowledge of the above mentioned differences between welded connections in hot-rolled and cold-formed sections a research programme has been carried out at the Institute TNO for Building Materials and Building Structures. This research is part of the general research programme "Connections in Cold-formed Sections". The research programme "Mechanical connections in Cold-formed Sections" (ref. |1|) which was presented at the Fourth International Specialty Conference on Cold-formed Steel Structures, also forms part of this study. The programme on welded connections is partly sponsored by the European Coal and Steel Community and the Dutch industry.

## 2. RESEARCH PROGRAMME

### 2.1 General

The aim of this research was to obtain uniform design rules for welded connections in thin sheet and to investigate the interaction of cold-forming and welding.
The research programme was carried out in three parts:

- State of the art with respect to welded connections in thin sheet (ref. |2|).

- Welding technology. A literature study (ref. |3|) was carried out by the Metal Institute TNO.

- Design of welded connections. Recommendations are given for the design of spot - and fillet welded connections. For spot - welded connections this was done with the (lot of) information available from literature, while for fillet - welded connections complementary experimental research was carried out.

### 2.2 State of the art

This study (ref. |2|) indicated that:

- Spot and fillet welds are usually applied in structural design. Seam and butt welds do have more specific applications; for instance, with constructing barrels and pipes.
- In field arc-welded spot and fillet welds are applied while in shop resistance spot welding is the most important technique.

. Arc-welded connections generally are realized with covered electrodes. However, there is an increased use of gas-shielded arc-welding processes (TIG, MIG and MAG), because of better results .

. In foreign specifications mainly attention has been paid to spot-welded connections except for the AISI specification, edition 1968, which to some extent deals with fillet welds. The Swedish specification, edition 1973, most extensively deals with spot-welded sheet steel connections (failure modes, design formulas, testing of spot welds and design rules).

. Relevant publications (refs. |4|, |5|, |6| and |7|) are treating spot-welded connections (strength, failure modes and design formulas) and only the publications of investigations carried out at Cornell University (ref. |8|) are dealing with spot and fillet welds.

. In refs. |9| and |10| is concluded that the welding methods hardly affect the steel properties. If problems occur they generally are of structural kind. Welding cold-formed thin steel would not require specific steel qualities and welding methods. However, it was decided to check this statement for confirmation by the Metal Institute TNO.

## 2.3 Welding technology

The results of the literature study carried out by the Metal Institute TNO can be summarized as follows:

. From a metallurgical point of view:

- Strain ageing is the main factor affecting the mechanical properties. Recrystallization and quench ageing are measurable but can be neglected.
- Cold-formed materials are more susceptible to ageing after upsetting than after elongation.
- The nitrogen content is important with strain ageing, the aluminium killed steels prove to be less susceptible than the non-killed ones. However, acceptable toughnesses were met.

. From the structural point of view

- With thicknesses smaller than 8 mm and steel grades with relatively low nitrogen and phosphorus contents and a small grain size (DIN 17100 classes 2 and 3) hardly any problems occur (ref. 10 and 11 ).
- With thicknesses smaller than 2 mm it was not possible to find any affection of strength or toughness of the investigated steel grades by the welding process (ref. |9|). These steel grades were: Fe 310 (rimned), Fe 410 (killed) and Fe 510 Ti, steel grades according to Euronorm 27-74 (the numbers 310, 410 and 510 are related to the specified tensile strength in $N/mm^2$).
- Acceptable joints can be obtained with the generally used welding processes. Dependent to design requirements it can be necessary to specify the material, the welding method (low heat-input is to be preferred), the qualification of welders and the inspection.

For structural design purposes can be concluded that welding of cold-formed thin steel sections does not substantially affect the mechanical properties of the steel. This is very important since the increase of the yield strength as a result of cold-forming is of great economical use for cold-formed sections. The improvement of the static properties can be considerable as is shown in fig. 1. In the Draft Dutch Regulations for Tubular Structures and the Draft European Recommendations for Thin-Walled Cold-Formed Members the design yield strength may be calculated with the formula of Lind and Shroff (ref. |12|). At each corner of $90^\circ$ the yield strength can be raised to the ultimate tensile strength of the parent material over a length of 5 or 7 times the thickness (see formula: factor c). The increase of yield strength at the corners is averaged over the cross-section. In formula:

$$\Delta\sigma_{e_{eq}} = c\alpha\ (\sigma_t - \sigma_e)\ \frac{nt^2}{A}$$

$$\sigma_{e_{eq}} = \sigma_e + \Delta\sigma_{e_{eq}}$$

where: $\sigma_{e_{eq}}$ = average design yield strength of a section

$\Delta\sigma_{e_{eq}}$ = averaged increase of yield strength

$\sigma_e$ = specified yield strength parent material

$\sigma_t$ = specified tensile strength parent material

n = number of corners

t = thickness

A = cross-sectional area

c = coefficient; c = 5 for press-braking

c = 7 for cold-rolling

$\alpha$ = coefficient depending on angle of bending; $\alpha$ = 1 for $90^\circ$

To verify the statement that the increase of yield strength at the corners is not reduced by welding, tests have been carried out at the Institute TNO for Building Materials and Building Structures on T-connections and Warren type connections of cold-formed and hot-rolled rectangular hollow sections (refs. |13| and |14|). The results are shown in figs. 2 and 3. The strengths of the connections in cold-formed sections were evaluated using the measured stub-column yield stress (see fig. 1). The differences between hot-rolled and cold-formed sections were negligible and therefore the use of the Lind and Chroff method is a safe approximation of the design strength ($\sigma_{e_{eq}} < \sigma_{e_{stub\ column}}$ : see fig. 1).

## 3. SPOT-WELDED CONNECTIONS

Generally spot-welded connections are applied in sheet steel with thicknesses from about 0.5 to 3.0 mm. In the simpliest form it concerns a single lap joint (see fig. 4). From literature it was concluded that spot welds show failure modes similar to connections with mechanical fasteners as bolts, rivets and screws (ref. |1|). These failure modes are (see fig. 5):

- Inclination failure. This failure mode occurs with relatively thin sheet and is to be considered as a combination of shear and tension of the weld.
- Shear failure. Compared with inclination failure, shear failure occurs with thicker sheet. In design recommendations, inclination and shear failure are often treated together. Ultimate load formula:

$$P_{us} = \frac{\pi}{4} d_s^2 \sigma_u$$

where: $P_{us}$ = ultimate shear load

$d_s$ = design value diameter of spot weld. The best approximation for $d_s$ is (refs. |4|, |5|, |6| and |7|):

- fusion welding → $d_s = 5 + 0.5\ t$
- resistance welding → $d_s = 5\sqrt{t}$

$t$ = thickness thinnest sheet (see fig. 4: $t = t_2$)

$\sigma_u$ = measured ultimate strength sheet material

. Tearing and bearing at contour of weld. Tearing at one side of the weld and piling up of the material at the opposite site. Ultimate load formula:

$$P_{ut} = 3{,}5\ t\ d_s\ \sigma_u$$

where: $P_{ut}$ = ultimate load with tearing and bearing

. Edge failure. This failure mode is dependent on the edge distance of the weld. Ultimate load formula:

$$P_{ue} = 1.4\ t\ e\ \sigma_u$$

where: $P_{ue}$ = utlimate load with edge failure

$e$ = edge distance of the weld

. Net section failure. Ultimate load formula:

$$P_{un} = A_n\ \sigma_u$$

where: $P_{un}$ = ultimate load with net section failure

$A_n$ = net cross-sectional area

To arrive at design strength formulas it is necessary to distinguish between failure modes upon their deformation capacity. All failure modes mentioned except for shear failure, possess sufficient deformation capacity. Thus will be recommended:

- To calculate the design strengths as follows:

$$P_{ds} = \frac{\pi}{4} d_s^2 \, \sigma_e$$

$$P_{dt} = 3{,}5 \, t d_s \sigma_e$$

$$P_{de} = 1{,}4 \, t \, e \, \sigma_e$$

$$P_{dn} = A_n \sigma_e$$

where: $P_{ds}$, $P_{dt}$, $P_{de}$ and $P_{dn}$ = design strengths with resp. shear, tearing and bearing, edge failure and net section failure

$\sigma_e$ = specified yield strength parent material

- To demand:

$$P_{ds} \geq 1{,}25 * \begin{vmatrix} P_{dt} \\ P_{de} \\ P_{dn} \end{vmatrix}$$

- To prescribe qualification shear failure tests according to fig. 6 with:

$$R_m = R - k.s$$

where: R = characteristic strength

$R_m$ = mean value of test results

k = factor dependent on number of tests (minium 4)

s = standard deviation of test results

- To demand that the actual strength should be greater than the calculated strength or:

$$R \geq P_{ds}$$

Proceeding this way it is asssured that shear failure shall not occur but is is also a check if the connections are well designed and if the right welding parameters have been chosen. Additional to these design requirements, rules for constructional details like edge and row distances, number of spot welds in load direction etc. have to be drafted.

## 4. FILLET-WELDED CONNECTIONS

### 4.1 General

In paragraph 2.2 it was mentioned that with respect to fillet-welded connections information was only available from an extensive research programme of Cornell University (ref. |8|). Basic variables in this research were:

- Double strap joints (see fig. 7). The cover plates used were flat sheet and channel sections.
- Transverse and longitudinal fillet welds with which the weld lengths were varied.
- Joints arc-welded with covered electrodes, in field and in shop.

It was concluded that:

. Weld shear failure does not occur since the stress resisting area of the weld is not as regular or easy to define as with hot-rolled sections.

. Failure modes observed were:

  - plate tearing at the contour of the weld, and
  - transverse tearing of the cover plates.

. Ultimate load formulas could be given for transverse and longitudinal fillet-welded connections.

However, it should be noted that:

. The type of connection investigated was a symmetrical one. Eccentricity caused by loading does not occur and inclination failure can not occur.

. The applied welding process and the use of specific electrodes resulted in considerable weld throat areas. In normal practice smaller weld throat areas can occur. In other words, weld shear failures have to be considered.

. The dimensions of the test specimen were not varied to investigate geometrical influences.

The foregoing has lead to the following research programme:

- tests on single lap joints transversely welded (see 4.2.1) longitudinally welded (see 4.2.2) and both transversely and longitudinally welded (see 4.2.3).
- tests on T-joints of section and strip (see 4.3.1) and of connections between sections (see 4.3.2).
- tests on complete connnections (see 4.3.3).

The steel grade used - unless otherwise specified - was cold - reduced, commercial steel Fe P 00 (Euronorm 32-66). Typical mechanical proporties: $\sigma_e = 200$ N/mm$^2$, $\sigma_t = 310$ N/mm$^2$, A5 = 25%.

## 4.2 Tests on single lap joints

### 4.2.1 Transversely welded specimen

These test series were started with preliminary tests emanating from:

- Test specimen as shown in fig. 8. The dimensions were kept constant: width b = 90 mm, thickness t = 1.58 mm.
- Uncoated and hot-dip galvanized sheet. In literature often it is stated that with resistance spot welding and correct welding parameters similar results can be achieved for galvanized sheet (a.o. ref. |15|).
- Different weld lengths $\ell_w$ = 20, 30, 40, 65 and 90 mm.
- Two welding processes. The uncoated sheet was welded with the argonarc process (TIG) while the galvanized sheet was arc-welded with covered electrodes.

The results of these preliminary tests are shown in fig. 9 together with the results of the 1st and 2nd series of tests. After discussing the latter series general conclusions will be drawn. With the 1st and 2nd series of tests the following parameters were included:

- The thickness t (t = 3.1 mm). This is an important parameter because of the failure mode (inclination combined with weld shear) and the weld throat dimension.
- The width b of the plates. Except for b = 90 mm (1st series) also b = 180 mm (2nd series) combined with weld lengths $\ell_w$ = 40, 60, 80, 130, 150 and 180 mm was investigated.
- Uncoated sheet was welded with the TIG-process and with covered electrodes.

With the 3rd series of tests were varied:

- The welding parameters and especially the electrode diameter. A weld throat thickness equal or greater than the sheet thickness was achieved. This allowed for a comparison with the Cornell tests.
- The test specimen were arc-welded with covered electrodes.
- The dimensions of the test specimen, width b = 90 mm, thickness t = 3.0 mm and weld length $\ell_w$ = 20, 30, 40, 65, 75 and 90 mm.

The design of the tests were such that one parameter was varied while the others were kept constant. The influence of the variation on the other parameters was observed and the following conclusions drawn:

- With galvanized sheet the strength of the welds is not significantly lower than with uncoated sheet. However, in tests the deviation of results was higher caused by the fact that making a sound weld with galvanized sheet is more difficult.

- Concerning the welding processes applied, the results for the argonarc welded specimen were slightly better compared with similar specimen welded with covered electrodes.

- Failure modes observed were inclination failure combined with weld shear, weld tearing and partly plate tearing at contour of weld (see fig. 8).

- The throat dimension of the weld is important. The results of the 3rd series of tests are better (see fig. 9) than the results of the other series of tests. Welding thin sheet does not guarantee a weld throat dimension which equals or exceeds the sheet thickness. One has to take care of well-chosen welding parameters to arrive at those weld throat dimensions!

- The deformation capacity of transversely welded specimen is small except of course in case of yielding of the cover plates outside the welded region. Nevertheless, the restricted deformation capacity of transversely welded specimen appeared to be sufficient to achieve full cooperation of transverse and longitudinal welds.

. Concerning the dimensions of the specimen:

- The thickness t is important with respect to the weld throat dimension. The sheet thickness also influences the failure mode. With thinner sheet inclination failure primarily occurs while with thicker sheet failure intends to weld shear.

- The width b appeared to be not important. The difference in results of the 1st and 2nd series was not significant.

. The weld length $\ell_w$: In spite of a considerable deviation of results (mainly caused by variations of weld throat dimensions) it was pointed out that with increasing ratio $\ell_w/b$ the ratio $P_u/t\ell_w\sigma_u$ (see fig. 9) is decreasing.

. From the results of fig. 9 the following ultimate strength formula was obtained:

$$R_m = t\,\ell_w\sigma_u(1 - 0.3\,\frac{\ell_w}{b})$$

where: $R_m$ = mean value ultimate strength of test results

$t$ = thickness thinnest connected member

$\sigma_u$ = measured ultimate strength of members

$\ell_w$ = length of weld

$b$ = width

The mean value of the test results of Cornell is also presented in fig. 9. The influence of the ratio $\ell_w/b$ in the Cornell tests was smaller than in the present test series. So, the Cornell research team proposed to neglect the influence of $\ell_w/b$ and to use the following ultimate strength formula: $R_m = t\,\ell_w\,\sigma_u$.

. All 56 test results were evaluated statistically to arrive at a characteristic strength R (with a tolerance limit of 5%):

$$R = 0.8\,t\,\ell_w\sigma_u\,(1 - 0.3\,\frac{\ell_w}{b})$$

Although with designing the characteristic strength R could be used, in normal practice the yield strength $\sigma_e$ is used. Since for most steel grades holds: $\sigma_e$ = 0.7 à 0.9 $\sigma_u$, the following design strength formula is proposed:

$$P_{d_{tw}} = t\,\ell_w\sigma_e\,(1 - 0.3\,\frac{\ell_w}{b})$$

where $P_{d_{tw}}$ = design strength transverse fillet weld

$\sigma_e$ = specified yield strength connected members

### 4.2.2 Longitudinally welded specimen

Since the parameters mentioned before with the transversely welded specimen also are of importance with longitudinally welded specimen, two series of tests were carried out investigating:

- . Testspecimen as shown in fig. 10. The dimensions were kept constant except for the thickness t (1st series - t = 1.58 and 3.1 mm, 2nd series - t = 3.0 mm).
- . Different weld lengths $\ell_w$ = 20, 40, 60, 80, 90, 100 and 120 mm.
- . Two welding processes, the argonarc process and arc-welding with covered electrodes. In the 1st series both processes were applied and in the 2nd series only the latter one.
- . The difference between the 1st and 2nd series concerned the welding parameters. With the 2nd series similar welding parameters have been chosen as with the 3rd series of the transversely fillet welded specimen to achieve a weld throat dimension which equals or exceeds the thickness of the sheet.

The results of these two series of tests are shown in fig. 11 and give rise to the following conclusions:

- . The welding processes applied did not yield significant differences in test results.
- . Failure modes observed, were (see also fig. 10):
  - Plate tearing at contour of the weld and weld shear. For the thinner plates these failure modes were accompanied by out of plane distortion and weld peeling. These failure modes happen with small weld lengths.
  - Transverse plate tearing. This is the basic failure mode for longer welds
- . The difference between the two series of tests was negligible. Thus, for longitudinal fillet welds the throat dimension of the weld is of minor importance compared with transverse fillet welds. This holds for thin sheet thicknesses and in this study thicknesses $\leq$ 3.1 mm were investigated.
- . The deformation capacity is small expecially with the smaller weld lengths. However, the deformation capacity is larger than with transverse fillet welds. In general the deformation capacity will be only then sufficient when the cover plates are able to yield.

. Concerning the failure mode "plate tearing at contour of the weld and weld shear" the influence of the weld length $\ell_w$ was evident.

. From the results of fig. 11 the following ultimate strength formulas were derived:

$$(1) \quad R_m = 2t\,\ell_w \sigma_u (0.9 - 0.45\,\frac{\ell_w}{b}) \qquad \text{- weld failure -}$$

$$(2) \quad R_m = 0.95t\,b\,\sigma_u \qquad \text{- plate failure -}$$

. All 42 test results were evaluated statistically to arrive at characteristic strengths:

$$R = 0.8 \times 2t\,\ell_w \sigma_u\,(0.9 - 0.45\,\frac{\ell_w}{b})$$

$$R = 0.9\,t\,b\,\sigma_u$$

The proposed design strength formulas are:

$$P_{d_{\ell_w}} = 2t\,\ell_w \sigma_e\,(0.9 - 0.45\,\frac{\ell_w}{b}) \qquad \text{- weld failure -}$$

$$P_{d_{\ell_w}} = 0.9\,t\,b\,\sigma_e \qquad \text{- plate failure -}$$

where: $P_{d_{\ell_w}}$ = design strength longitudinal fillet weld

4.2.3 Longitudinally and transversely welded specimen

Finally, the tests on thin sheet connections were completed with tests on single lap joints both longitudinally and transversely welded. The aim of these tests was to find out how the two weld types cooperated. The next serie of tests was carried out:

. Test specimen as shown in fig. 12. The dimensions were kept constant.

. Different combinations of weld lengths: $\ell_1$ = 20, 40, 60, 90 and 120 mm
$\ell_2$ = 20, 30, 40, 65, 75 and 90 mm

. Welding with covered electrodes, weld throat $\geq$ thickness sheet.

The results of these tests lead to the following conclusions:

. Similar failure modes as with the foregoing test series were met (see fig. 12).

. The deformation capacity of the welds allows full cooperation which means that the ultimate strength formulas of transversely resp. longitudinally welded specimen can be added, which results in:

$$R_m = t\,\sigma_u \left| \ell_2 (1-0.3 \frac{\ell_2}{b}) + 2\,\ell_1 \,( 0.9 - 0.45 \frac{\ell_1}{b} ) \right|$$

This formula is conservative since the "negative" effects of the separate test series are also added and it is not realistic to add the characteristic strengths of the separate test series to achieve a characteristic strength for this connection. Moreover this formula holds as long as transverse plate tearing does not occur. Thus a conservative estimation of the design strength is:

$$P_{d_{t\ell_w}} = t\,\sigma_e \left| \ell_2 \,(1 - 0.3 \frac{\ell_2}{b}) + 2\,\ell_1 \,(0.9 - 0.45 \frac{\ell_1}{b} ) \right|$$

$$P_{d_{t\ell_w}} = 0.9\ t\ b\ \sigma_e$$

where: $P_{d_{t\ell_w}}$ = design strength transversely and longitudinally welded specimen

4.3 Tests on T-joints

4.3.1 T-joint of section and strip

The results of tests on this type of connection were compared with the results of transversely welded single lap joints. Moreover, a comparison with effective width formulas of hot-rolled sections was possible. Firstly preliminary tests were carried out with:

. Test specimen as shown in fig. 13. The dimensions of the section were kept constant.

. Dimensions of the strip: thickness t = 1.5 and 3.1 mm
width b = 30, 60 and 100 mm

. Connections one- sided arc-welded with covered electrodes; welded along the entire width b; weld throat dimensions > thickness strip.

Further a series of tests was carried out to check the observations of the preliminary tests. Besides the parameters varied in the preliminary tests, it was also investigated:

- Testspecimen: rectangular hollow section - 100 x 40 x 3 mm
  channel section - 100 x 50 x 3 mm

- Dimensions of the strip: thickness t = 3.0 mm
  width b = 30, 60, 80 and 90 mm

The results of all tests are given in fig. 14.
From these test series it could be concluded that:

- Failure modes observed are:
  - Failure of the strip (see fig. 15),
  - Failure of face of chord section (see fig. 16),
  - Failure cross-section of chord (see fig. 17).

  Because of properly chosen welding parameters weld failure dit not occur as a basic failure mode.

- The deformation capacity of the failure modes observed is considerable. For failure of the chord face this is shown in fig. 14a.

- The stiffness of the connection increases with the width b of the strip (fig. 14a).

- Effective width ($b_t$) formulas (effective length of weld) for thick specimen proved to be not correct for thin members (Dutch Standard NEN 2062: $b_t = 5t_1 + 2t_2$).
  With ratios $\frac{b}{b1} < 0.8$ failure of the strip or failure of the chord face occurred. Failure of the strip was compared with failure of transversely welded sheet connections (see ultimate strength formulas). Failure of chord face could be approximated by a modified yield line theory (see appendix III).
  With ratios $\frac{b}{b1} \geq 0.8$ at the beginning the load is transferred to the chord wall directly, then tearing starts at the ends of the welds (see fig. 14a) followed by failure of the strip or failure of the chord face.

- The following ultimate strength formulas were obtained:

- failure of strip $R_m = tb\sigma_u \; (1-0.3 \frac{b}{b_1})$
- failure of chord face $R_m = 4t_1^2\sigma_u \; (1+2 \frac{b}{b_1})$

$\frac{b}{b_1} < 0.8$

For ratios $\frac{b}{b} > 0.8$ these formulas may be used substituting $b = 0.8\ b_1$. Care has to be taken that under service conditions tearing at the ends of the welds does not occur (see fig. 14a).

- Failure cross-section of chord, $R_m$ determined by bending and shear. Since this is not dealing with connection behaviour this failure mode will not be discussed further.

Where: $R_m$ = mean value ultimate strength test results

$t$ = thickness strip

$t_1$ = thickness chord face

$\sigma_u$ = measured ultimate strength strip/chord face

$b$ = width of strip

$b_1$ = width of chord section

$\ell_w$ = length of weld

. The number of tests (18) and i.e. the number for each failure mode does not allow a statistical evaluation of test results to arrive at a formula for the characteristic strength. The approximation of the ultimate load ($P_u$) by the ultimate strength formulas ($R_m$) as presented in fig. 14 is quite satisfactory. Therefore a similar approach as described on page 11 is proposed to arrive at the following design strength formulas:

$$P_{d_{ss}} = t\ b\ \sigma_e\ (1 - 0.3 \frac{b}{b_1}) \qquad \frac{b}{b_1} < 0.8$$

$$P_{d_{ss}} = 4\ t_1^2\ \sigma_e\ (1 + 2 \frac{b}{b_1}) \qquad \frac{b}{b_1} \geq 0.8\text{: substitute } b = 0.8\ b_1$$

where: $P_{d_{ss}}$ = design strength T-joint of section and strip

4.3.2 T-joint of two sections

With these tests on T-joints between sections (similar tests as described in 4.3.1, strip replaced by section) were investigated:

. Testspecimen:

- preliminary tests: chord section + brace section
  (See fig. 18) ⊔ -100x50x3 + ⊔ -30x30x3
  ⊔ -60x30x3
  ⊔ -80x40x3
- $1^{st}$ series of tests: chord section ⊔ -100x40x3, similar brace sections
- $2^{nd}$ series of tests: chord sections ⊔ -100x60x4 and □ -100x100x3 : similar brace sections

. All joints were tested in tension and compression.

. Welding with covered electrodes, weld throat $\geq$ thickness thinnest member.

The results of these tests are given in fig. 19. The following conclusions could be drawn:

. Failure modes observed, are:

- Failure brace section
  in tension: tearing brace flanges above the welds
  in compression: yielding flanges brace section
- Failure face of chord section
  in tension: tearing chord face
  in compression: excessive deformation chord face
- Failure wall of chord section
- Failure chord cross-section

Failure often is a combination of these failure modes and is occampanied by large deformations of the chord cross-section. Weld shear failure was not observed.

- All failure modes observed showed a considerable deformation capacity (see fig. 19a).
- The stiffness of the connection increased with increasing width b of the brace section (fig. 19a).
- With failure of the chord face the ultimate load in tension is attained after very large deformations of the connection (see fig. 19a). Often this is caused by secondary effects raising the strength. These effects are not incorporated in the ultimate strength formulas. This explains the difference in results between the ultimate load $P_u$ and the predicted strength $R_m$ with connections loaded in tension and failure of the chord face (see fig. 19).
- The following ultimate strength formulas were obtained:
  - failure chord face: $R_m = 4t_1^2\,\sigma_u\,(1 + 2\,\frac{b}{b_1} + \frac{h}{2(b_1-b)})$ ; $\frac{b}{b_1} < 0.8$ (see appendix III)
  - failure brace flanges: in tension $R_m = t\,\sigma_u 2h$, in compression $R_m = t\,\sigma_y 2h$ ; $\frac{b}{b} > 0.8$
  - failure chord cross-section, $R_m$ determined by bending and shear.

where: $R_m$ = (predicted) mean value ultimate strength of connection

$t$ = thickness brace section

$t_1$ = thickness chord face

$b$ = width of brace section

$b_1$ = width of chord section

$h$ = height of brace section ($\equiv$ width of flanges)

$\sigma_u$ = measured ultimate strength brace/chord section

$\sigma_y$ = measured yield strength brace section.

- The number of tests (24) does not allow a statistical evaluation of test results for each failure mode to arrive at characteristic strength formulas. However, with respect to the observations mentioned in the foregoing paragraphs, the following design strength formulas are proposed (also see page 11 and page 16):

$$\frac{b}{b_1} < 0.8 - P_{d_{bc}} = 4t_1^2 \; \sigma_e \; \left(1 + 2\frac{b}{b_1} + \frac{h}{2(b_1 - b)}\right)$$

$$\frac{b}{b_1} \geq 0.8 - P_{d_{bc}} = t \; \sigma_e \; 2h$$

where: $P_{d_{bc}}$ = design strength T-joint brace/chord sections

$\sigma_e$ = specified yield strength

4.3.3 Complete connections

At last connections between sections as indicated in fig. 20 have been considered. With these tests were investigated:

- Testspecimen as shown in fig. 20, loaded in tension:
  - preliminary tests : chord ⊔-100x50x3 + brace ⊔-80x40x3
  - 1e series of tests : chord ⊔-100x60x4 + brace ⊔-60x30x3 and ⊔-80x40x3

    chord ◫-100x100x3+ brace ⊔-60x30x3 and ⊔-80x40x3

- All joints were supplied with longitudinal (side) fillet welds resp. transverse (end) and longitudinal (side) fillet welds. The joints were arc-welded with covered electrodes, weld failures prevented.

The results of these tests are given in fig. 21. The following could be concluded:

- Failure modes observed, are:
  - Failure brace section: bending and tension followed by tearing of the section just outside the connection.
  - Failure chord section: bending and torsion, the loading does not act in the shear centre of the section

**Note: Failure of the connection did not occur. The values of the test results were lower than those predicted with the ultimate strength formulas for single lap joints (see 4.2.2 and 4.2.3).**

- It was demonstrated that these thin-walled cold-formed open profiles possess little torsional rigidity. Load application in the shear centre of the section appeared to be very important.
- With designing this type of connections, loaded in tension or in compression, it seems reasonable to use the design strength formulas for single lap joints.

## 5. CONCLUSIONS

Summarizing, the most important conclusions are:

- With properly chosen welding parameters, acceptable welded connections in thin-walled members can be obtained with the generally used welding processes.
- The improvement of static properties of a section as a result of cold-forming is not reduced by welding.
- From existing knowledge about the structural behaviour of spot-welded connections design strength formulas are proposed.
- For fillet-welded sheet steel connections design strength formulas are derived from the results of Cornell University and from experimental research at TNO.
  Except for sheet steel, fillet-welded connections of cold-formed sections were investigated at TNO and recommendations for design are given.
  Additional to flat specimen, fillet-welded connections of cold-formed sections were investigated at the TNO and recommendations for design are given.
- The results of research at TNO (ref. |16|) should contribute to design rules of welded connections in the European Recommendations, similar to the results of research on connections with mechanical fasteners.

APPENDIX I - REFERENCES

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|4| G. Franz, "Das Tragverhalten von Punktschweissverbindungen", Schweisstechnik 1966 - Heft 10.

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|10| H.J. Veit, "Probleme des Schweissens im Bereich kaltgeformten Profile", Schweissen und Schneiden 1968 - Heft 3.

|11| J. Ruge and H. Wösle, "Schweissen an kaltverformten Teilen - Entwicklung und Beurteilüng aus heutiger Sicht", Der Stahlbau 1977 - Heft 9.

|12| N.C. Lind and D.K. Shroff, "Utilization of cold work in light gage steel", August 1971, Paper presented at First International Specialty Conference on Cold-formed Steel Structures.

|13| J. Wardenier and C.H.M. de Koning, "Static tensile tests on T-joints in structural hollow sections, Report of IBBC-TNO and TH-Delft.

|14| J. Wardenier and C.H.M. de Koning, "Ultimate static strength of welded lattice girder joints in rectangular hollow sections", 1975, Report of IBBC-TNO and TH-Delft.

|15| E.A. Green and J.J. Riley, "Resistance spot welding galvanized steel of thicknesses 0.022 to 0.138 in.", April 1963, Paper presented at AWS 44th Annual Meeting in Philadelphia, Pa.

|16| F. Soetens, "Welded connections in cold-formed sections", final report to be published in 1980, Report of IBBC-TNO.

APPENDIX II - NOTATION

$A$ = cross-sectional area

$A_n$ = net cross-sectional area

A5 = elongation standard tensile coupon test

$b$ = width of specimen

$b_t$ = effective width

$b_1$ = width of chord section

$c$ = coefficient (see 2.3)

$d_s$ = diameter of spot weld

$e$ = edge distance of weld

$h$ = height of brace section (≡ width of flanges)

$k$ = factor dependent on number of tests

$\ell_w$ = length of weld

$\ell_1$ = longitudinal fillet weld length

$\ell_2$ = transverse fillet weld length

$n$ = number of tests

$P$ = load

$P_d$ = design strength

$P_{de}$ = design strength with edge failure

$P_{dn}$ = design strength with net-section failure

$P_{ds}$ = design shear strength

$P_{dt}$ = design strength with tearing and bearing

$P_{d\ell_w}$ = design strength longitudinal fillet weld

$P_{d_t}$ = design strength transverse fillet weld

$P_{d_{t\ell w}}$ = design strength transversely and longitudinally welded specimen

$P_{d_{bc}}$ = design strength T-joint brace/chord sections

$P_{d_{ss}}$ = design strength T-joint of section and strip

$P_u$ = ultimate load

$P_{ue}$ = ultimate load with edge failure

$P_{un}$ = ultimate load with net-section failure

$P_{us}$ = ultimate shear load

$P_{ut}$ = ultimate load with tearing and bearing

$R$ = characteristic strength of connection, determined from tests

$R_m$ = mean value strength, determined from tests

$s$ = standard deviation of test results

$t$ = thickness

$t_1$ = thickness face of chord section

$t_2$ = thickness wall of chord section

$\alpha$ = coefficient (see 2.3)

$\sigma_e$ = specified yield strength

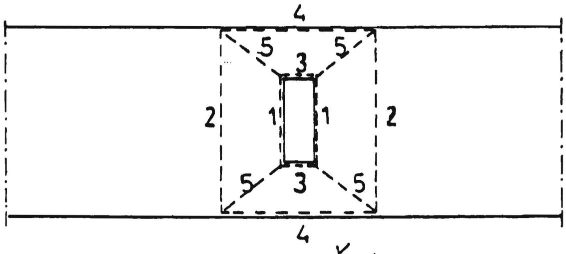
$\sigma_{e_{eq}}$ = average design yield strength of a section

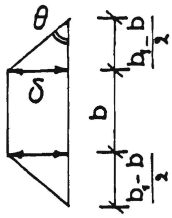
$\sigma_t$ = specified tensile strength

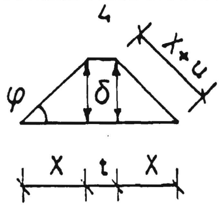
$\sigma_u$ = measured ultimate strength

$\sigma_y$ = measured yield strength

APPENDIX III - YIELD LINE APPROACH FAILURE CHORD FACE




T-joint section and strip, see fig. 13

top view chord face

Distribution of bending and normal forces in chord face:

- In transverse direction chord section relatively weak; contrarily in longitudinal direction stiff. Therefore along
  - yield lines (1) and (2): bending + normal forces
  - yield lines (3), (4) and (5): bending

- Bending: full plastic moment per unity of length $m_p = \sigma_e \frac{t_1^2}{4}$

  Bending + normal forces: reduced plastic moment per unity of length

$$m_1 = m_p \{ 1 - (\frac{\delta}{t_1} \cdot \frac{b_1}{b_1+b})^2 \} \qquad m_2 = m_p \{ 1 - (\frac{\delta}{t_1} \cdot \frac{b}{b_1+b})^2 \}$$

  and reduced normal force per unity of length

$$n_1 = n_p \{ \frac{\delta}{t_1} \cdot \frac{b_1}{b_1+b} \} \qquad n_2 = n_p \{ \frac{\delta}{t_1} \cdot \frac{b}{b_1+b} \}$$

  with $n_p = \sigma_e t_1$

- Energy executed along yield lines ($A_i$):

Yℓ 1: $2b\, m_1\, \phi + 2b\, n_1 u_1$

Yℓ 2: $2b_1 m_2\, \phi + 2b_1\, n_2 u_2$

Yℓ 3: $2t\, m_p\, \theta$

APPENDIX III (cont.)

$Y\ell$ 4: $2(t + 2X)\, m_p \theta$

$Y\ell$ 5: $4(X\theta + \frac{b_1 - b}{2}\phi)\, m_p$

. Energy by external load ($A_u$): $P.\delta$

. $\Sigma A_i = \Sigma A_u$

substitute: $\phi = \frac{\delta}{X}$ ; $\theta = \frac{2\delta}{b_1 - b}$ ; $u_1 + u_2 = u \approx \frac{\delta^2}{2X}$

$$P = m_p \left[ \frac{2b}{X} \{ 1 - (\frac{\delta}{t_1} \cdot \frac{b_1}{b+b_1})^2 \} + \frac{2b_1}{X} \{ 1 - (\frac{\delta}{t_1} \cdot \frac{b}{b+b_1})^2 \} + \right.$$

$$\left. + \frac{8t+16X}{b_1 - b} + \frac{2(b_1 - b)}{X} \right] + n_p b \, (\frac{\delta}{t_1} \cdot \frac{b_1}{b_1 + b}) \, \frac{\delta}{X}$$

with: $\frac{\delta}{t_1} \frac{b_1}{b+b_1} \leq 1$ and $b < b_1$

. Suppose: $X = \frac{1}{2}\sqrt{b_1(b_1 - b)}$ → minimum energy with bending and $\frac{\delta}{t_1} = \frac{b+b_1}{b_1}$

Approximated solution: $P = 16\, m_p \, (1 + 2\frac{b}{b_1} + \frac{t}{2(b_1 - b)})$

with $b < 0.8b_1$, $t << b_1$ } $P = 16\, m_p \, (1 + 2\frac{b}{b_1})$ (see page 15)

with brace sections : $t = h$ (see page 18)

. Ultimate strength formulas: $m_p = m_u$ and $n_p = n_u$

or substitute $\sigma_e = \sigma_u$ (yield → failure)

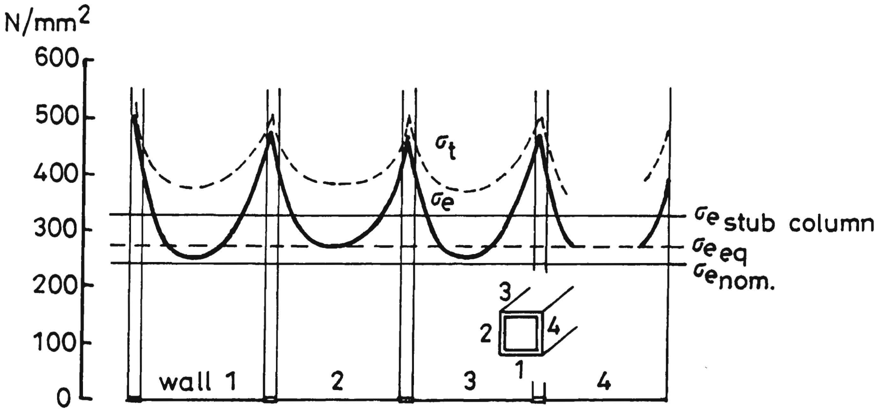



fig. 1 Measured values of $\sigma_e$ and $\sigma_t$ in a cold-formed rectangular hollow section 100 x 100 x 4 mm

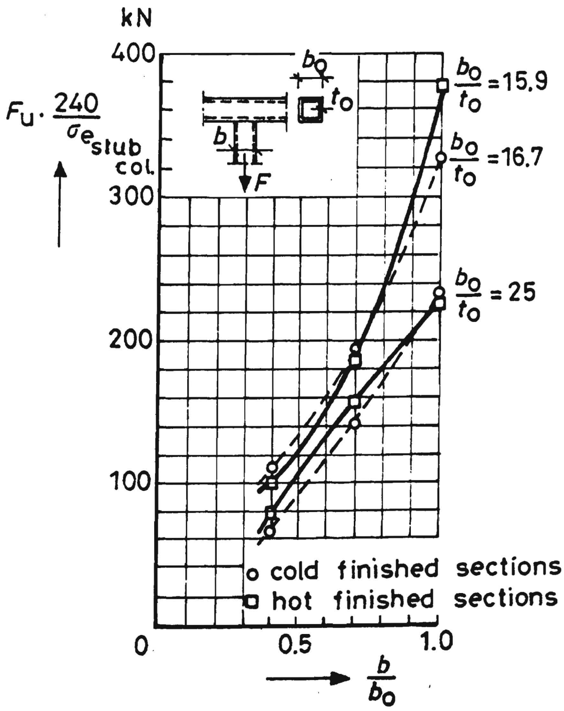



fig. 2 Test results for T-joints

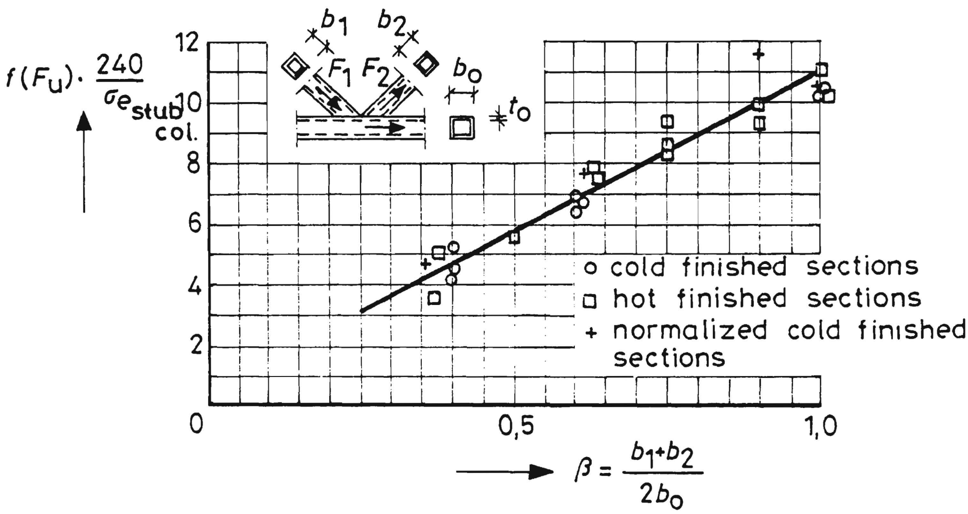



fig. 3 Test results for K - joints

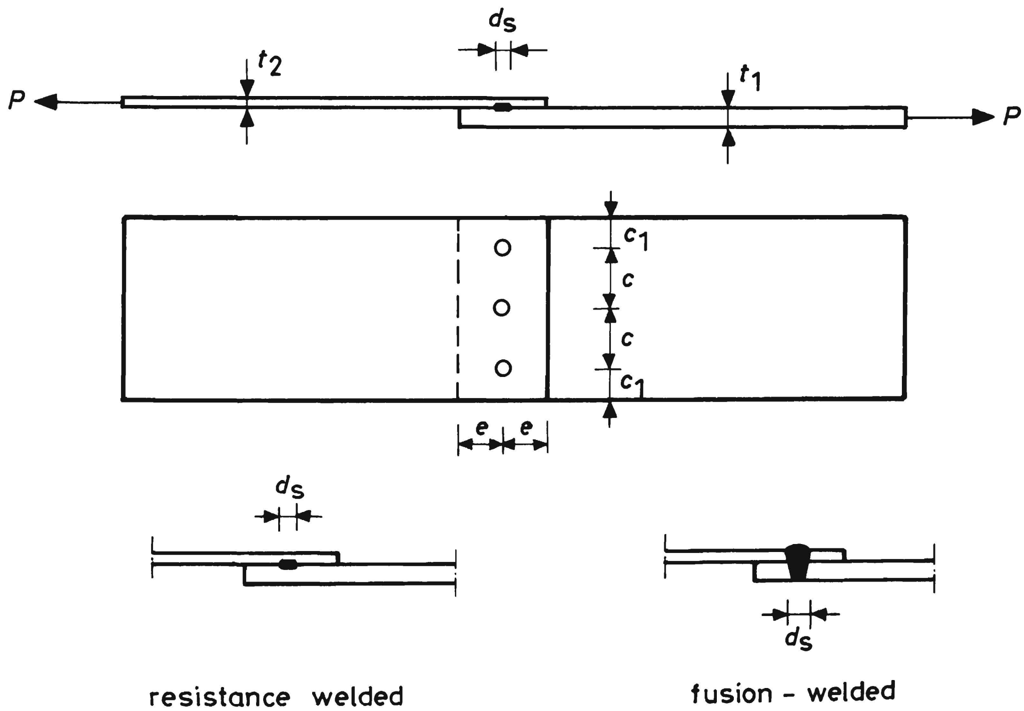



fig. 4 Single lap joint, spot welded

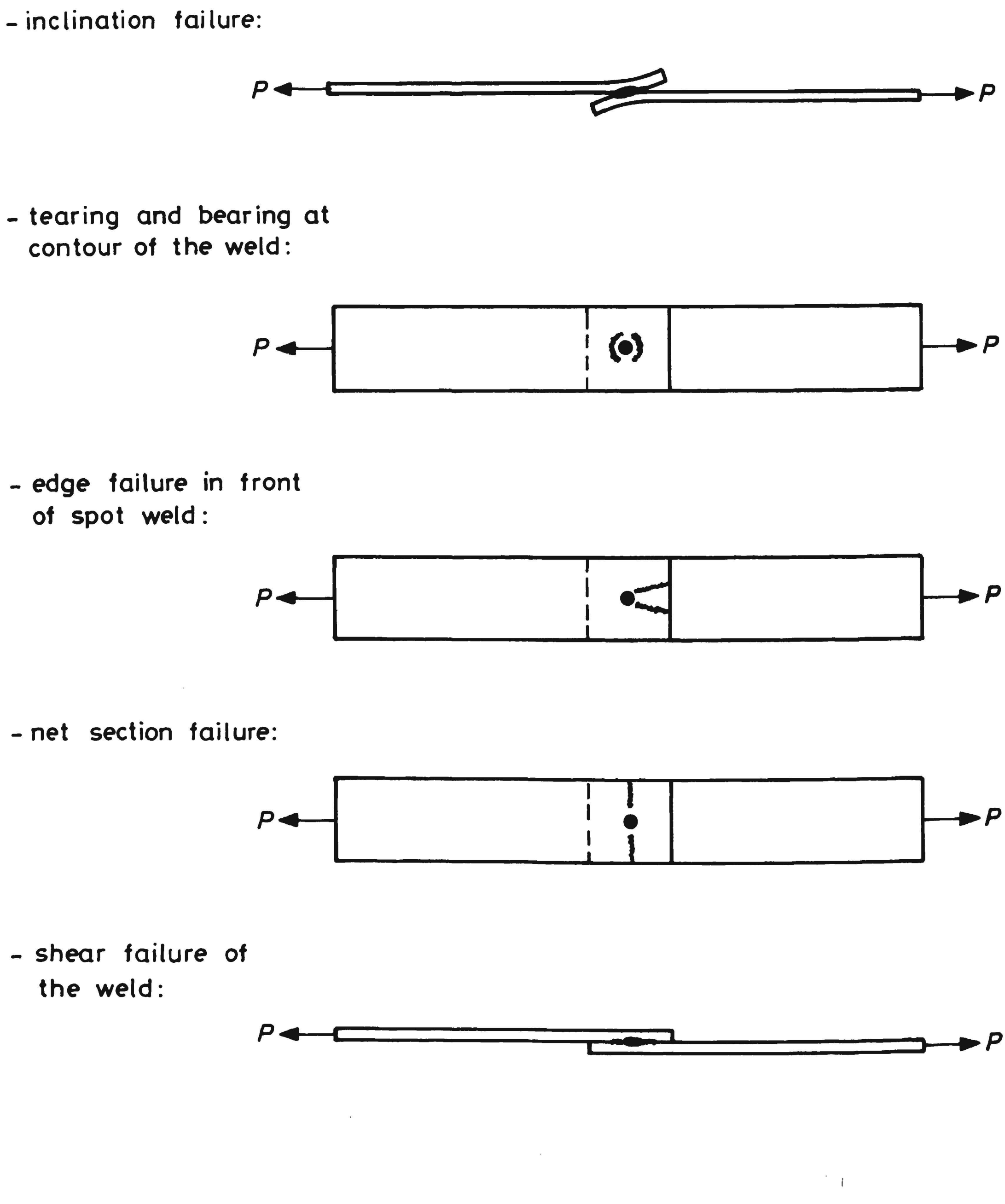
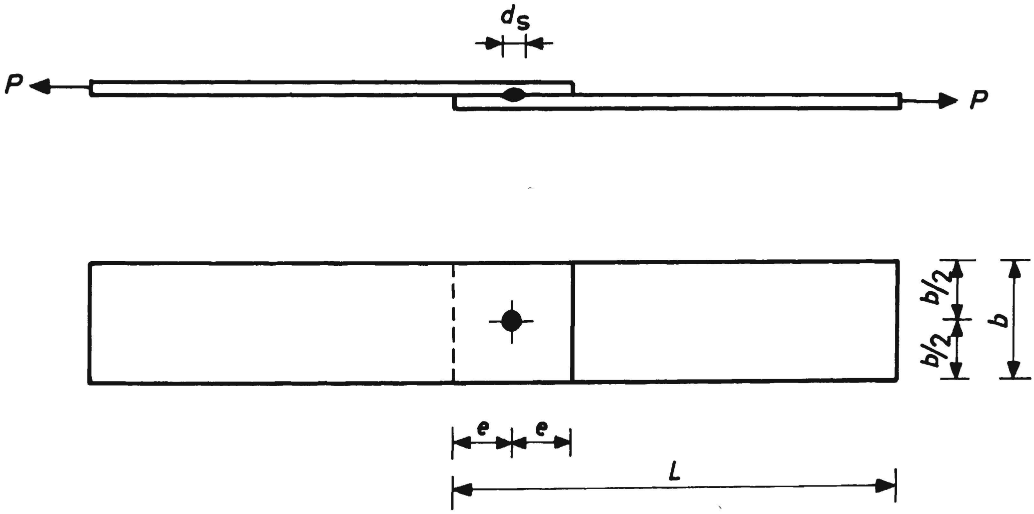



fig. 5 Failure modes spot welded single lap joints




$3.5\, d_s < e < 5.0\, d_s$ ; $b \approx b\, d_s$ ; $L = 400$ mm

fig. 6 Dimensions specimen for shear / inclination failure tests

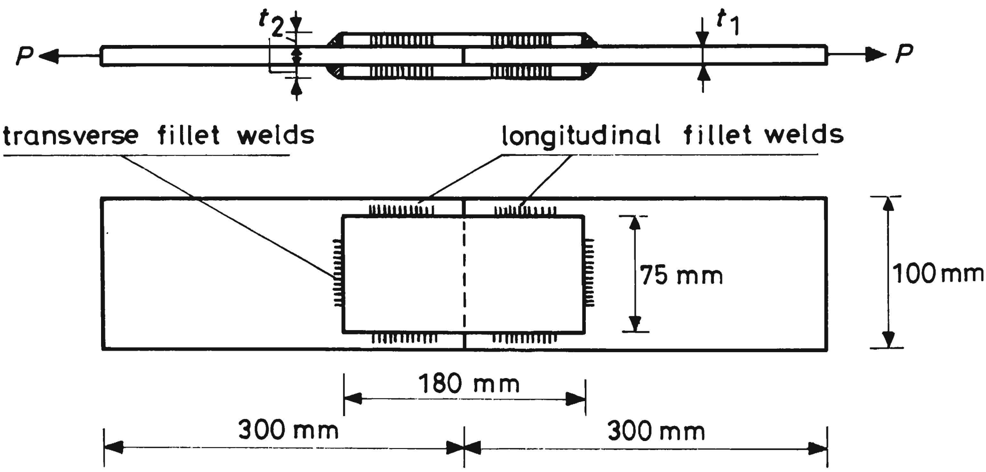



fig. 7 Double strap joint, fillet welded

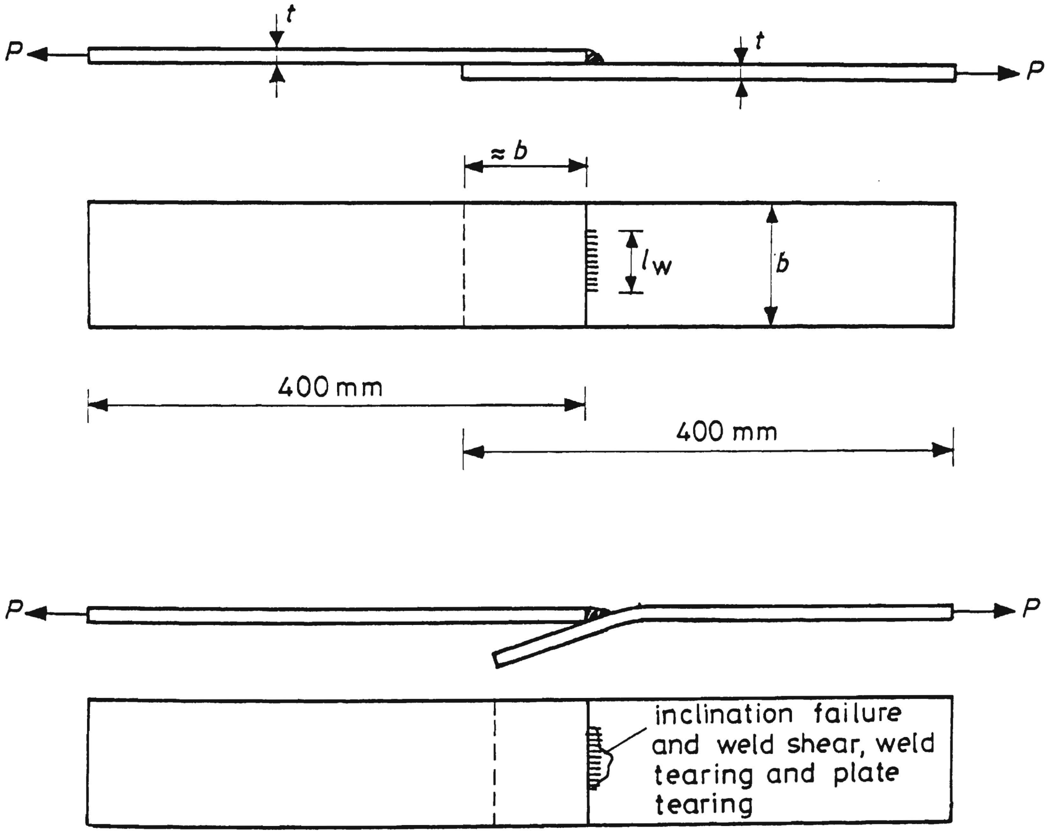
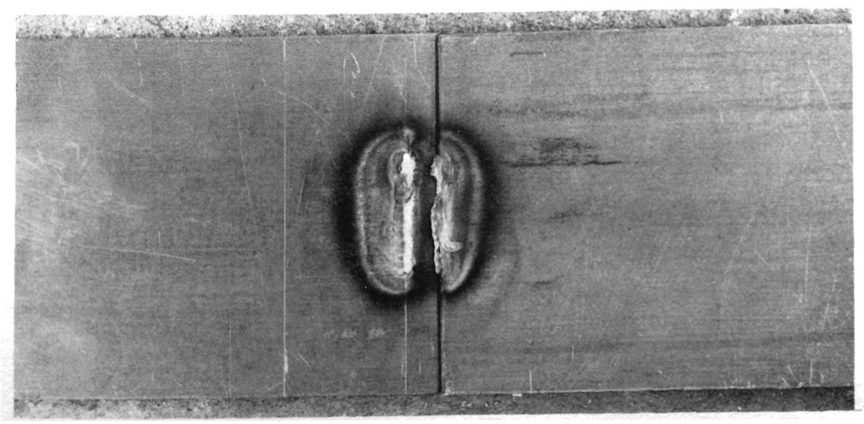



fig. 8 Single lap joint, transversely welded



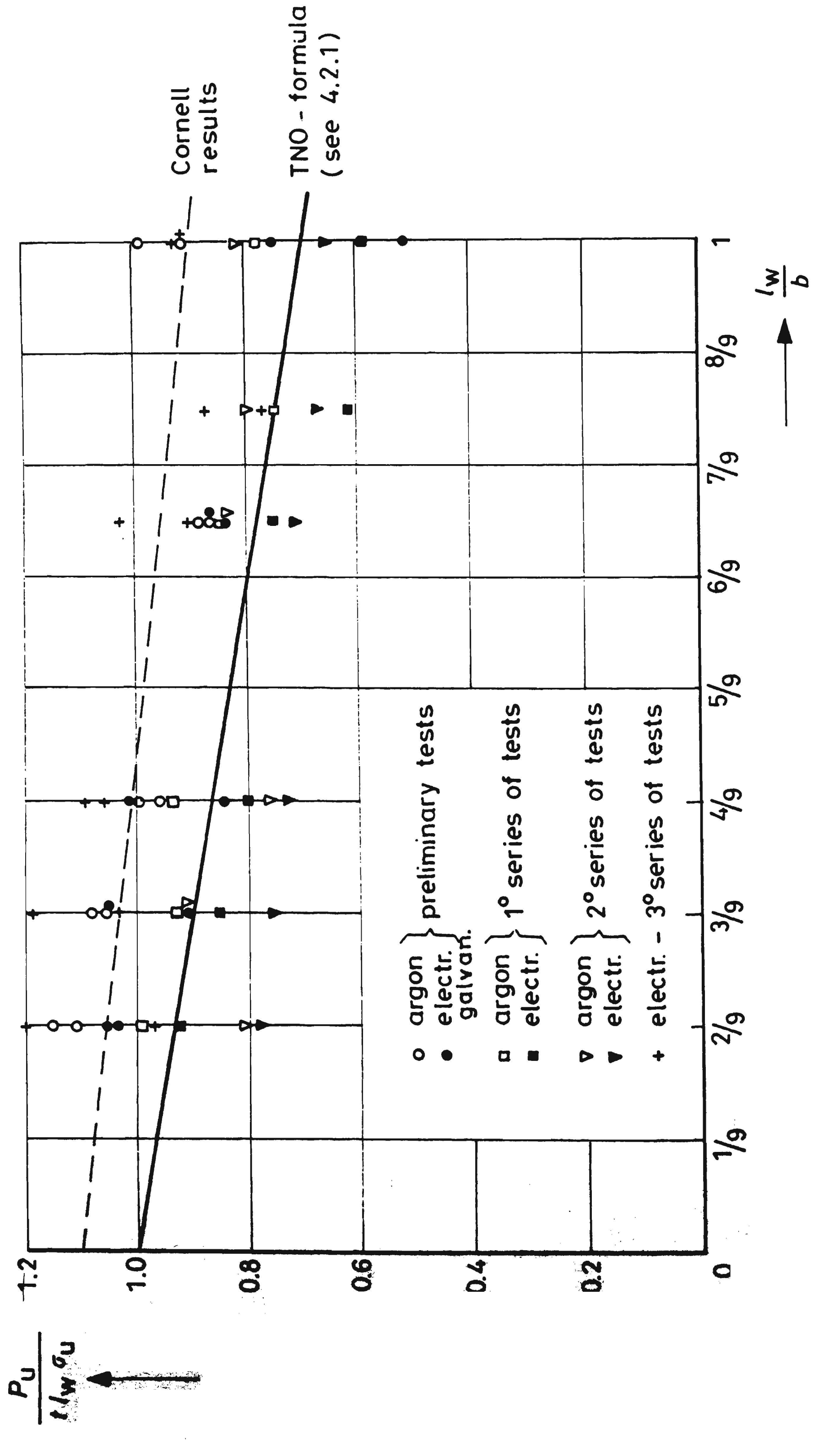



fig. 9 Test results single lap joints, transversely welded

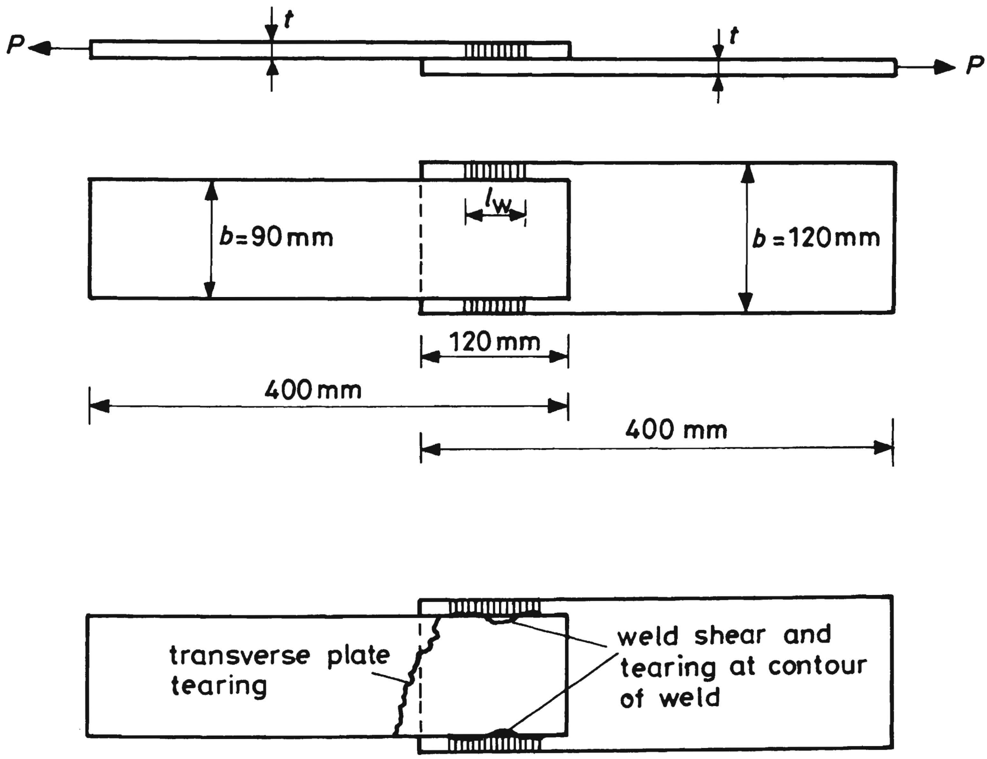



fig. 10 Single lap joint, longitudinally welded

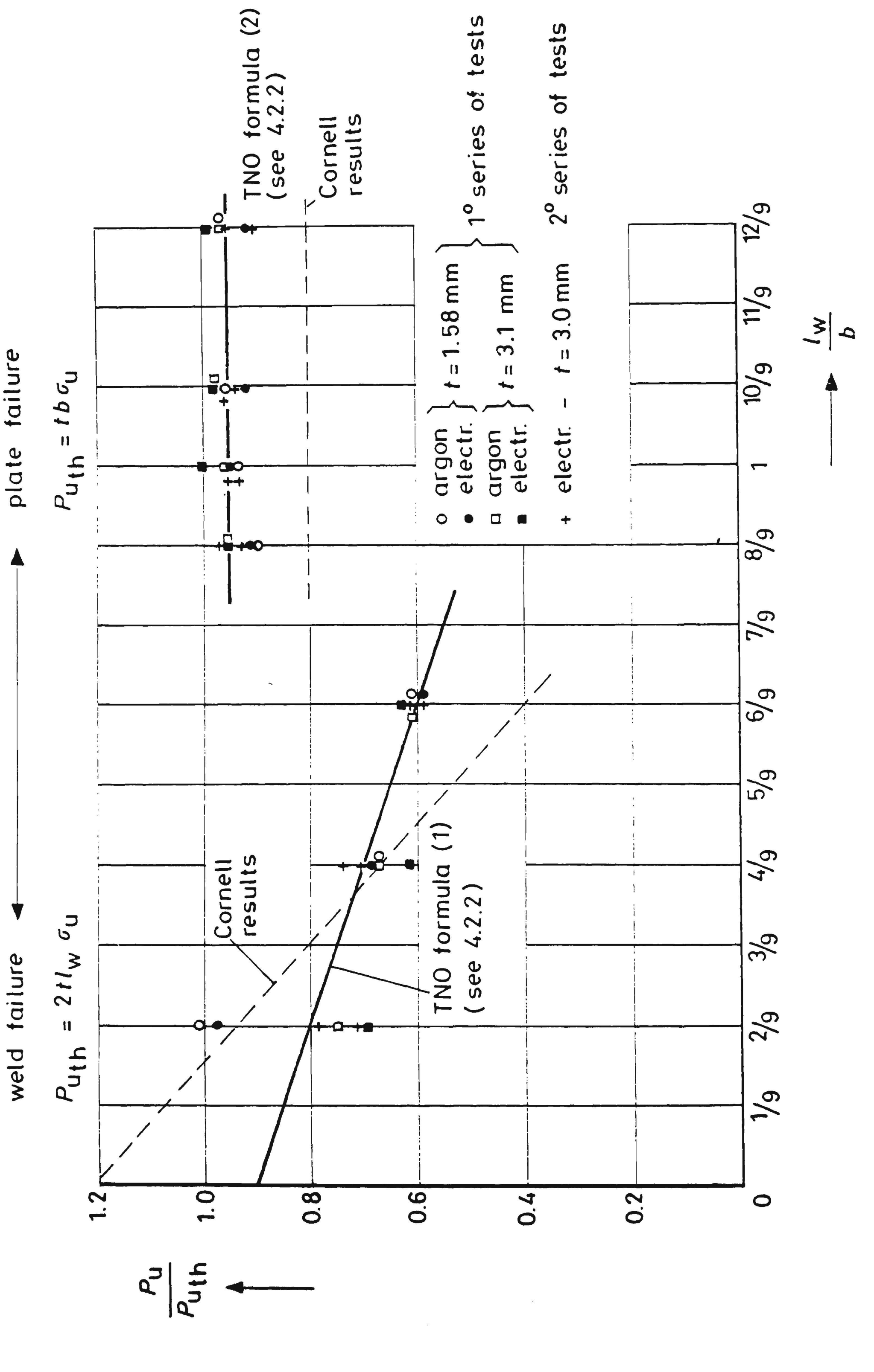



fig.11 Test results single lap joints, longitudinally welded

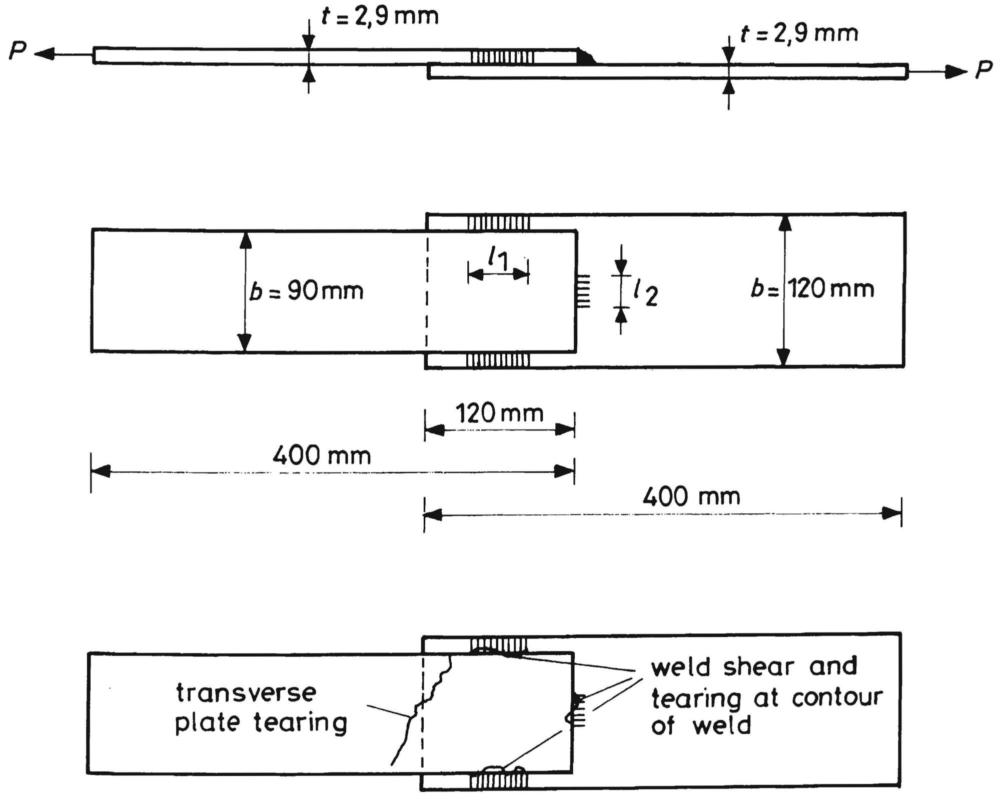



fig. 12 Single lap joint, longitudinally and transversely welded

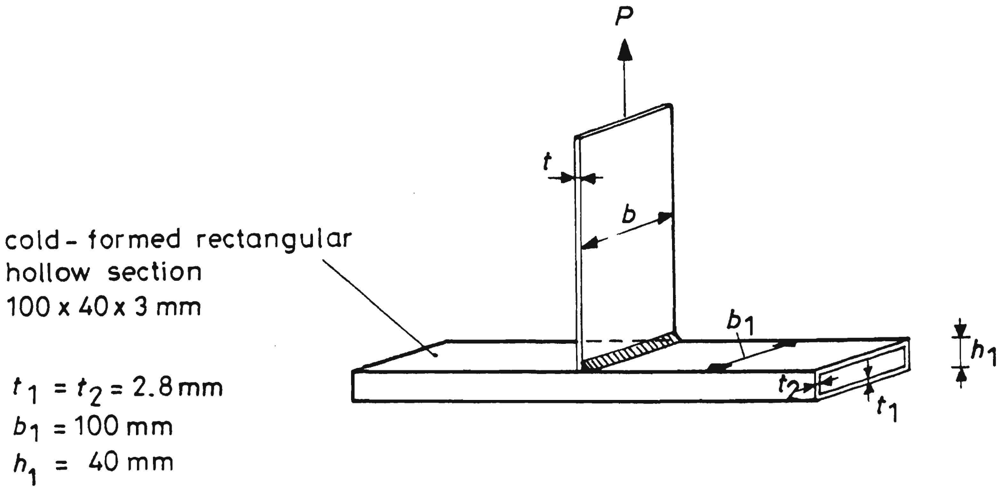



fig. 13 *T*-joint, section and strip

| b [mm] | $b_1$ [mm] | t [mm] | $t_1 = t_2$ [mm] | $P_u$ [kN] | $R_m$ [kN] | failure mode | connected memers |
|---|---|---|---|---|---|---|---|
| 30 | 100 | 1.5 | 2.8 | 14.7 | 13.1 | tearing strip | |
| 60 | 100 | 1.5 | 2.8 | 25.7 | 23.6 | " | |
| 100 | 100 | 1.5 | 2.8 | 30.0 | 29.2 | " | |
| 30 | 100 | 3.1 | 2.8 | 22.3 | 24.9 | chord face | 100x40x3+ strip |
| 60 | 100 | 3.1 | 2.8 | 32.7 | 34.2 | " | |
| 100 | 100 | 3.1 | 2.8 | 38.8 | 40.4 | " | |
| 30 | 100 | 3.0 | 2.8 | 23.1 | 24.9 | chord face | |
| 60 | 100 | 3.0 | 2.8 | 38.1 | 34.2 | " | |
| 80 | 100 | 3.0 | 2.8 | 39.9 | 40.4 | " | 100x40x3+ strip |
| 90 | 100 | 3.0 | 2.8 | 35.9 | 40.4 | " | |
| 30 | 100 | 3.0 | 3.0 | 16.8 | - | cross-section chord | |
| 30 | 100 | 3.0 | 3.0 | 17.1 | - | " | |
| 60 | 100 | 3.0 | 3.0 | 16.9 | - | " | |
| 60 | 100 | 3.0 | 3.0 | 6.2 | - | " | |
| 80 | 100 | 3.0 | 3.0 | 21.5 | - | " | 100x50x3+ strip |
| 80 | 100 | 3.0 | 3.0 | 23.2 | - | " | |
| 90 | 100 | 3.0 | 3.0 | 17.6 | - | " | |
| 90 | 100 | 3.0 | 3.0 | 23.8 | - | " | |

Fig. 14: Test results of T-joints, section and strip

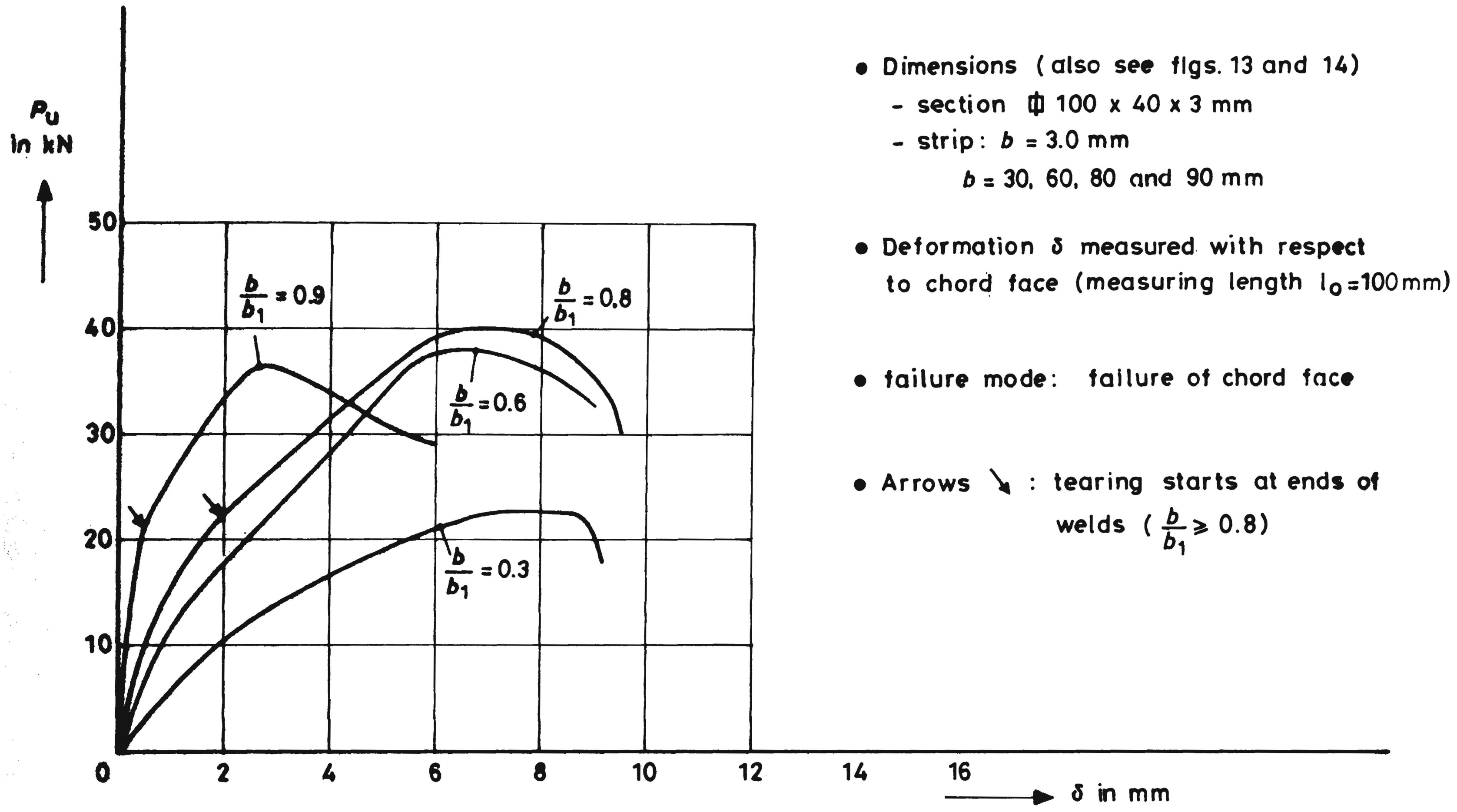



**fig. 14a** *P*-δ diagram *T*-joint, section and strip (also see fig. 14)

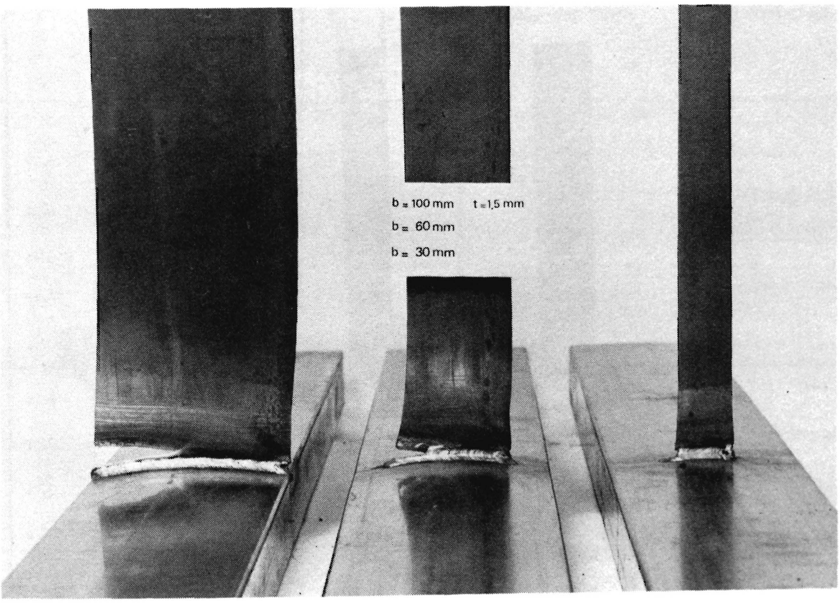



Fig. 15: T-joint, failure of strip

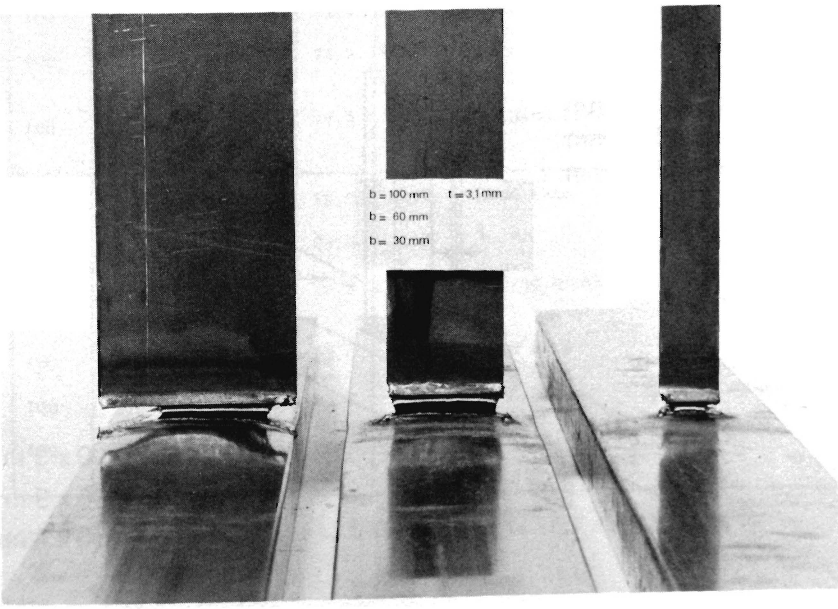



Fig. 16: T-joint, failure of face of chord section

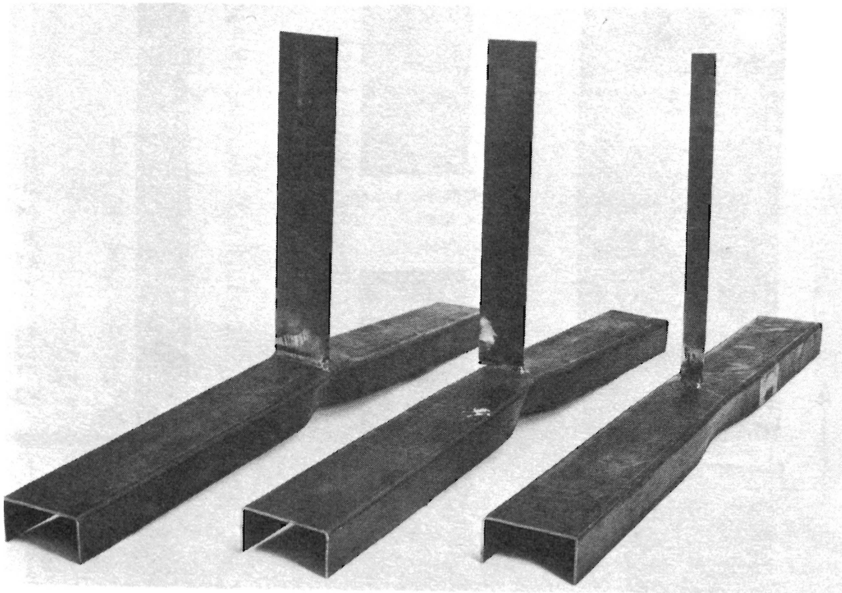


Fig. 17: T-joint, failure of chord cross-section

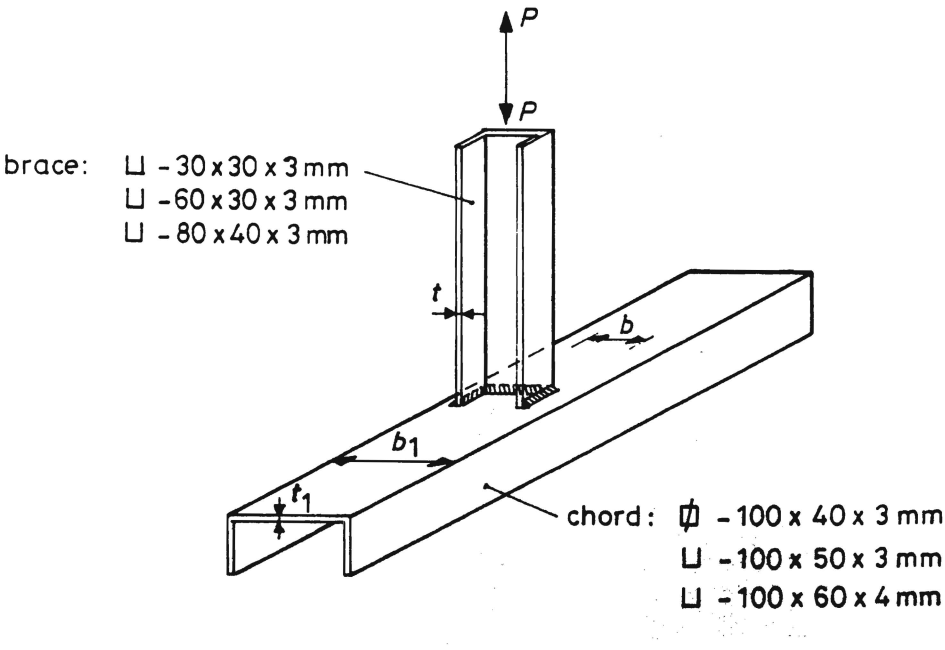



fig.18 T - joint, section and section

| b<br>\|mm\| | $b_1$<br>\|mm\| | t<br>\|mm\| | $t_1 = t_2$<br>\|mm\| | $P_u$<br>\|kN\| | $R_m$<br>\|kN\| | failure mode | connected members |
|---|---|---|---|---|---|---|---|
| 30 | 100 | 3.0 | 3.0 | 28.1 | - | cross-section chord | tension |
| 60 | 100 | 3.0 | 3.0 | 24.2 | - | " | |
| 80 | 100 | 3.0 | 3.0 | 31.3 | - | " | ⊔-100x50x3+⊔(see fig.18) |
| 30 | 100 | 3.0 | 3.0 | 26.0 | - | " | |
| 60 | 100 | 3.0 | 3.0 | 27.6 | - | " | compression |
| 80 | 100 | 3.0 | 3.0 | 35.2 | - | " | |
| 30 | 100 | 3.0 | 2.8 | 63.4 | 28.0 | chord face | |
| 60 | 100 | 3.0 | 2.8 | 64.4 | 40.4 | " | tension |
| 80 | 100 | 3.0 | 2.8 | 100.1 | 83.5 | tearing brace flanges | ⊞-100x40x3+⊔ |
| 30 | 100 | 3.0 | 2.8 | 40.8 | 28.0 | chord face | |
| 60 | 100 | 3.0 | 2.8 | 39.5 | 40.4 | " | compression |
| 80 | 100 | 3.0 | 2.8 | 56.7 | 49.9 | yielding brace flanges | |
| 30 | 100 | 3.0 | 4.0 | 61.9 | 47.3 | chord face | |
| 60 | 100 | 3.0 | 4.0 | 60.0 | 67.1 | chord face/cross-section | tension |
| 80 | 100 | 3.0 | 4.0 | 75.2 | - | chord cross-section | ⊔-100x60x4+⊔ |
| 30 | 100 | 3.0 | 4.0 | 54.1 | 47.3 | chord face | |
| 60 | 100 | 3.0 | 4.0 | 75.2 | 67.1 | chord face/cross-section | compression |
| 80 | 100 | 3.0 | 4.0 | 79.3 | 49.9 | yielding brace/chord cross section | |
| 30 | 100 | 3.0 | 2.8 | 58.0 | 22.1 | chord face | |
| 60 | 100 | 3.0 | 2.8 | 83.6 | 31.6 | " | tension |
| 80 | 100 | 3.0 | 2.8 | 96.3 | 83.5 | tearing brace/chord face | ⊞-100x100x3+⊔ |
| 30 | 100 | 3.0 | 2.8 | 37.0 | 22.1 | chord face | |
| 60 | 100 | 3.0 | 2.8 | 50.3 | 31.6 | " | compression |
| 80 | 100 | 3.0 | 2.8 | 48.5 | - | chord wall/cross section | |

Fig. 19: Test results of T-joints, between sections (see also fig. 18)

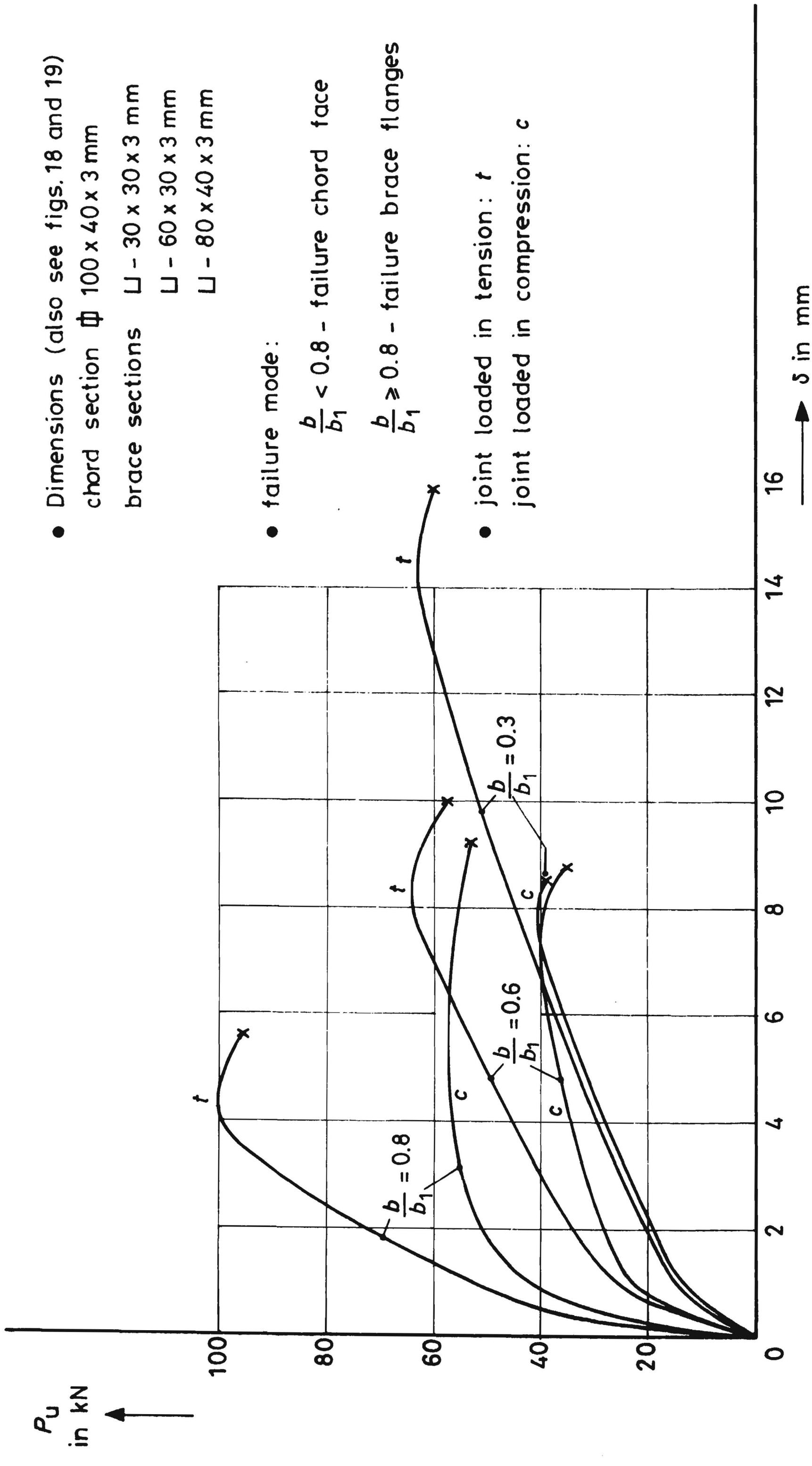



fig.19a $P - \delta$ diagram $T$-joint of two sections

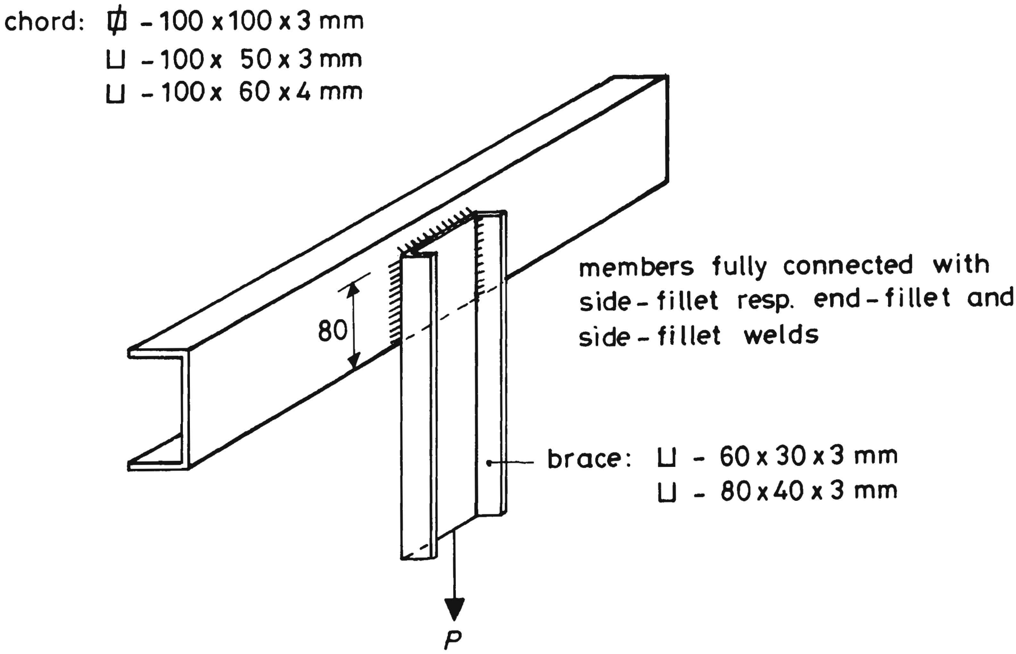



fig. 20 Complete connections

| chord | brace | weld | $P_u$ kN | $R_m$ kN | failure mode |
|---|---|---|---|---|---|
| ⊔-100x50x3 | ⊔-80x40x3 | side | 65.4 | - | bending/torsion chord section |
| | | side | 65.5 | - | " |
| | | side/end | 63.2 | - | " |
| | | side/end | 64.0 | - | " |
| ⊔-100x60x4 | ⊔-60x30x3 | side | 77.1 | - | bending/tension brace section |
| | | side/end | 69.8 | - | " |
| | ⊔-80x40x3 | side | 86.9 | - | " |
| | | side/end | 87.0 | - | " |
| ◫-100x100x3 | ⊔-60x30x3 | side | 72.5 | - | " |
| | | side/end | 69.3 | - | " |
| | ⊔-80x40x3 | side | 60.6 | - | " |
| | | side/end | 72.1 | - | " |

Fig. 21: Test results complete connections (see fig. 20)